NATO Security through Science Series - B:
Physics and Biophysics

Detection and Disposal of Improvised Explosives

Edited by
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Springer

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This publication is supported by: The NATO Programme for Security through Science

Detection and Disposal of Improvised Explosives

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Detection and Disposal of Improvised Explosives

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Published in cooperation with NATO Public Diplomacy Division

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PREFACE

These proceedings contain the presentations and results of several discussions of the workshop on "Detection and Disposal of Improvised Explosives" held in St.-Petersburg, Russia, September 7-9, 2005. This Advanced Research Workshop was the fourth event concerning Detection of Explosives in connection with counter terrorism.

After the first three workshops, dealing with vapor and trace detection, electronic nose detection and detection of bulk explosives, this workshop was devoted to the detection of Improvise Explosives including:

- Methods of detection of Improvised Explosives (IE).
- Methods of detection of Improvised explosives devices (IED).
- Disposal and safe handling of ID and IED.

The treatment of detection methods may be divided in the following groups:

- Overview about the different methods;
- Trace- and vapor detection;
- Electromagnetic methods;
- Neutron methods;
- Laser techniques.

Because of different definitions of Improvised Explosives the participants of the workshop agreed after some discussions with the following definition:

An Improvised Explosive (IE) can be any chemical compound or mixture capable of an explosive reaction. They are normally easily prepared by a knowledgeable layman under simple conditions. Components of IE are typically inorganic salts containing molecular bound oxygen like nitrates, chlorates or perchlorates etc. or organic compounds with nitro-, nitamine- or nitrate-groups or peroxides. Admixtures of military or commercial explosive materials are also used.

From the chemical point of view IE can be divided into the following types:

- Salts containing chemical groups with oxygen (like nitrates, chlorates or perchlorates etc.) in mixtures with combustible substances like carbon-hydrogen compounds.

- Commercial available or “home-made” organic substances with nitro-, nitroxy- or nitramine-groups.
- Both types in mixtures with commercial or military explosives.
- Peroxides.

It would be also possible, to use liquid explosive mixtures for terrorist purposes, because they are easy available, though their storage and application are rather difficult. Examples are mixtures of nitric acids with combustible liquids or nitro compounds.

An Improvised Explosive Device (IED) is an explosive charge of improvised, commercial or military explosive or mixtures, which is equipped with a home-made (non standard) or with a professional detonator.

A large palette of methods and sensors are known and applied with more or less success to the detection of commercial or military explosives, depending on the conditions and circumstances.

Because of the various types of compositions of the IE it was an open question, if suitable detection methods and sensors would ever be available for IE. Assuming all used IE have the same chemical components like military or commercial explosives, all known detection methods may be more or less successful. But in practice terrorists are also using explosive compositions, which are not common in the commercial or military applications. They contain unusual components, which are not used elsewhere because of different reasons: low long-term stability, low safety properties in handling, or low performance. The advantages of using these explosive formulations are either the possibility to produce them “at home” in a simple way like in a “home made” production or they are available as commercial products.

Important examples are peroxides like TATP and oxygen- salts like nitrates, chlorates and perchlorates without or in mixtures with combustible materials (e.g. black powder).

During the workshop a wide range of explosive detection methods and sensors for detection and a large variety of “Improvised Explosives” formulations and devices were discussed. From the chemical point of view only some functional groups of the formulations are prerequisites for their possible explosive character. Therefore the sensors have to identify in general “only” these functional groups, which are identical between military-, commercial- or improvised explosives. Therefore in principle all detection methods, which are suitable for detection of military and/or commercial explosives, may be also suitable for IE or IED. It is an open question, whether known detection methods shall have the same performance in the detection of IE.

In addition there are some IE, like peroxides and oxygen-salts and their mixtures with or without combustible materials, where applicability of known detection methods must be tested. Oxygen-salts have no vapor-pressure: this is a disadvantage for some detection methods. Unlike these salts, peroxides like TATP have high vapor pressure, which makes detection easier. The exchange of detection experiences during the workshop resulted in the conclusion: TATP is detectable.

The disposal and safe handling of IE and IED do not present a great problem in principle. The material should be disposed by already well-established disposal protocols and procedures, keeping in mind that stability and life-time may be less than those of ordinary explosives.

It would be very helpful, if the material were identified. However, in all cases disposal material should be handled in the same manner as unexploded ordnance or munitions, because stability cannot be guaranteed.

An additional problem exists, if IE or other explosive materials can be detected in a standoff scenario, but this item should be treated in a next Advanced Research Workshop at the end of this year.

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ACKNOWLEDGEMENT

I thank my cochairman and his crew from the Khlopin Institute, St. Petersburg, Russia, for the organization of the International Advanced Research Workshop. It was the third ARW in the series of events about Detection of Explosives in connection with counterterrorism in St. Petersburg. The local organization was running in an approved way leading to a good success of the workshop.

Thanks also to the director of the Khlopin Institut, Prof. Dr. Rimski-Korsakov, for his support.

I thank all international colleagues from Russia and Nato Countries for their participation, presenting their contributions and participating in a very aktive diskussions, which has also influenced some remarks in the preface of this proceedings.

I thank the members of the Advisary Panel on Security Related Civil Science&Technology and its Programm director for the support and interest in this ARW.

Hiltmar Schubert

DISPOSAL OF IMPROVISED EXPLOSIVES AND –DEVICES

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Abstract. Because of logistic problems terrorists are using for there explosive attempts so-called "Improvised Explosives and Improvised Explosive Devices". The paper described the definition and composition of these materials including the design of the corresponding charges and concluded with the treatment of the disposal procedure.

1. Introduction

The expression "Improvised Explosives and –Devices" was created at the end of the 60ties of the last century, when global terrorism has started. Difficulties with the logistic support of controlled military and commercial explosive materials, terrorists were looking for inconspicuous resources in the normal trade. According to available "Cook-Books", "Home made explosives" were produced by terrorists from intermediate products for their objectives.

The presupposition was the availability of those materials, the easy preparation of the explosive materials and properties for a disaster after initiation or ignition.

The knowledge about suitable substances and how to produce such charges are available by literature (internet). Examples are "Terrorist's Handbook", "Anarchist Arsenal", "Black Book", "Home made Detonators" etc.

Unlike military explosives like TNT, RDX, PETN etc. the range of possible combinations will be very large: May be over 200 examples!

This is also the reason, why there are complications to detect them. Terrorists do not consider very much relative long lasting thermal stability and mechanical sensitivity of the explosive materials. These reduced properties have also consequences for the detection and especially for the disposal process.

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2. Definition of Improvised Explosives (IE) and Improvised Explosive Devices (IED)

Improvised Explosives (IE) are compounds or mixtures of compounds, which have explosive properties and should be relative easily prepared by layman under simple conditions (home made) using freely available chemicals and informations.

Military and commercial explosive materials may be also used in form of simple made charges.

Improvised Explosive Devices (IED) are explosive charges with IE-material in confined or unconfined shape, equipped with a commercial or improvised initiators. The initiator will be ignited by electric or mechanical means.

Such devices react like bombs with a detonation causing a blast wave and fragmentation of the surroundings. If the charge is confined also fragments of the material are formed. There are also examples, where the material is “only” deflagrated, causing also blast waves and fire with large destruction-effects if large amounts of material are involved (Example Sept 11).

It may be important belonging to the demolition output of a charge, that in a distance of more than 1-5 m the pressure wave of a deflagration or detonation will be of the same order. Otherwise the fragments of the confinement will be smaller and more dangerous by detonation.

3. Compositions of Improvised Explosives (IE)

In principle an explosive material consist of one or more chemical compounds which has enough oxygen to oxidize the remaining combustable substance. To realize a good combustion (Deflagration) the material has to be more or less homogeneous. If the combustion energy is very high a shockwave is created, which causes a detonation. The concentration of energy will be supported by high density and confinement.

If we follow the definition about IE mentioned above, the preparation of these substances or mixtures have to avoid complex chemical processes. The preparation must be a simple reaction or only blending.

Typical Improvised Explosives are (1) :

1. Salts with functional groups containing oxygen, like Nitrate, Chlorate, Perchlorate etc. in mixtures with combustable substances like C-H materials.
2. Commercial available organic substances with Nitro- Nitroxy- and Nitramine-compounds also in mixtures with CH containing materials (fuels)

3. Peroxides, which are easy to produce, like TATP or primary explosives.
4. Combustable fuels or dusts can be used together with the surrounding air- oxygen to produce an explosion (Deflagration). (Sept. 11)
5. Delaborated military explosives as an admixture to improvised explosives.
6. “Liquid explosives” being composed of nitric acid and Nitrocompounds or aromatic liquids. (Used in World War II in aerial bombs)

To detonate typical IE (except some Peroxydes, which have the function of primary explosives) a primary explosive is necessary confectioned in a detonator cup. If detonators are not available also initiating improvised primary explosives have to be produced. Because small amount are only necessary, for examples 0,8 g for one initiation of a charge the preparation is not too expensive but very dangerous. Examples for the preparation process will be found in literature mentioned above.

To detonate an insensitive explosive like Ammoniumnitrate-Fuel mixture a small additional high explosive charge is necessary beside the detonator cup.

4. Composition of Improvised Explosive Devices (IED)

Commercial detonators consist of a metal cup (Aluminium or Cupper) filled with a primary explosive (0,8g) like Lead azide, Mercury fulminate etc. and an electrical igniter (bridge wire detonator) or a fuse head. Improvised detonators are similar constructed with - for instance TATP – as primary explosive and with an electrical or mechanical ignition devices.

Sometimes the IED is fitted with a time-fuse or other arrangements.

5. Destruction of Improvised Explosive Devices (IED)

5.1 DESIGN OF EXPLOSIVE DEVICES

The design and placement of an IED is up to the imagination of the terrorist bomber,but for the detection and destruction (if no explosion follows) it is useful to know the most frequent designs of the charges and initiation devices.

IED can be contained in almost everything. The item must be carried or driven where the terrorist will place, so concealment or masking of the device will be necessary.

The outer container can be, but not limited to (2):

- Pipe Bombs – steel or plastic pipe sections with caps in nearly any configuration

- Belt with bags filled with ID, Backpack or Briefcase
- Service mail packages
- Vehicle Bomb
- Containers like fire extinguishers, propane bottles, trashcans, gasoline cans etc.

To increase the output of the charge, the explosive material is arranged in a metal case. The firing train consists of a fusing system, detonator and main charge. The activation of the firing train happens by

- an interval of time by a timer, pocket watch or electronic item.
- activation by the suicide bomber (Pull, tension release, booby-trap etc.
- sending a signal via radio frequency or hiffen wire from a remote location
- by changing the environment (temperature, pressure, light, sound or magnetic field)

5.2 THE DESTRUCTION PROCESS

If the terrorist action was prevented or terrorist bombs are found before the action was executed the destruction of the IED has to be carried out.

The awareness and behaviour against terror bombs are described in numerous data sheets and recommendations in nearly every country (3).

The disposal of IED follows well known and prescribed procedures by explosive ordnance disposal technicians, which are trained to accomplish this mission.

In most cases the properties and the explosive reaction of the charge are unknown the IED will be treated as an unexploded ordnance like a “Munition found”. Because Improvised Explosive Materials are involved with perhaps unstable properties, handling, transportation and destruction are very dangerous actions.

The first step of the destruction process before transportation of the charge will be the separation of the firing train, this is an imperative action. If necessary a remotely device should be used.

Sometimes it is necessary to analyze the composition of the IE and the concept of the firing train. To collect samples of the IE, a remote controlled device is necessary.

There are two possibilities for the destruction of the IED:

- Destruction of the charge by detonation or burning on a suitable place concerning the surroundings more or less nearby the IED was found.

  If it is not possible to cut the firing train, the detonation must be done on the place of discovery.

The Firing-place should have safety distances according to regulations in the different countries.

The distance depends on the amount of explosive:

Example: (4):

Amount of Explosives (kg)	Distance (m)
<2,0	45
2,0 – 4,5	55
4,5 – 9,0	70
9,0 – 13,5	80
13,5 – 18,0	85
18,0 – 25,0	95

The mentioned distances do not avoid a protection against fragments of possible confinement of the charge.

- To decrease the environmental stresses caused by detonation of terrorist charges underwater detonation may be recommended.
- For small charges like 1 kg heavy armed kettles are used, constructed to resist the detonation of the charge. These vessels are also used to investigate suspicious objects (airports or police stations).
- For larger charges a dismantling is recommended for further treatment of the material, depending on the special composition.

  For instance IE being composed of watersoluble substances likes Ammoniumnitrate may be treated by water, organic material may be treated by suitable solvents. The operation has to be done environmental friendly.

6. Post Explosion Activities

Experiences have shown, that in nearly all cases of explosions, residues of the exploding material can be found in more or less very small amounts. The analyses of these traces are important to know what explosive materials terrorists are using. Methods like mass-spectrometry of other trace-analysis methods are used.

7. Conclusion

The disposal of improvised explosives and –devices require no additional Research and Development activities, because the principle procedure in the case of “Disposal of Munition Found” or “Unexploded Ordnance” is well known and prescribed. Additional problems may occur, because of the unknown composition and behaviour of improvised explosives, especially if the material has an extreme sensitivity against thermal and mechanical stress.

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DETECTION OF IMPROVISED EXPLOSIVES (IE) AND EXPLOSIVE DEVICES (IED)

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Abstract. A brief description of existing and prospective techniques for detection of improvised explosives (IE) and improvised explosive devices (IED) is presented.

1. Introduction

Improvised explosive devices (IED) are devices, which contain at least one homemade component. IEDs can be divided into two classes:

1. IEDs that contain industrially manufactured explosives. Such IEDs may differ from standard explosive devices by presence of homemade detonators, triggering mechanisms, etc.
2. IEDs that contain improvised (homemade) explosives (IE). Such IEDs often also contain non-standard detonators etc.

Neutralization and disposal of IEDs is a difficult task:

1. Design and construction of the IED is unknown, therefore standard disposal methods, e.g. those used in demining, may be inapplicable. Before disposal of IEDs the sapper should use whatever methods are available to study its design; however one can never know in advance whether there is time for such a study (if, for example, the IED is equipped with a timer).

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2. The type, exact location and mass of the explosive charge may be difficult to determine by an external survey. Thus the chosen disposal method may turn to be inadequate.
3. Detonators and triggering mechanisms of IEDs may be unreliable and can be initiated at an unpredictable time.
4. IE used in IEDs may be very unstable, i.e. sensitive to external influences like shock, temperature, etc.

Figure 1. Components of an improvised detonator produced from a 23 mm shell fuse (photo from http://www.fsb.ru).

2. Improvised Explosives and Explosive Devices

High explosives that are most often used in IEDs can be split into five categories:

1. Industrially produced military explosives (TNT, C4 etc.). Such explosives are a) highly stable and have strictly regulated sensitivity to external influences; b) have rather high density (>1.5 g/cm^3), which is higher than the density of most common organic substances.
2. Industrially produced explosives used in civil applications (e.g. grammonite 50/50, ammonite) sometimes are a mechanical mixture of military ES (like TNT) with substances like ammonium. Such explosives a) are highly explosive, approaching by this parameter

military ES; b) usually have densities in the range 0.9-1.2 g/cm^3, which is close to densities of common organic substances; c) often contain marking agent, which facilitates detection of such ES by vapor analysis techniques.

3. Explosives prepared from easily available materials and used in civilian applications (igdanites, ammonals, etc.) Such explosives a) are easy to manufacture on the spot; b) components are cheap and available; c) are rather highly explosive (e.g. explosive capacity of igdanites is half of that of TNT); d) have average density in the range 0.8-1.1 g/cm^3, which is close to the density of common organic substances; e) have rather large minimum detonating mass (more than 1 kg; smaller amounts often do not produce stable shock waves); f) are often tightly packed to prevent evaporation of liquid components and to increase their shelf life.
4. Improvised (homemade) explosives used by terrorists who have access to military explosives (for example, the so-called "Chechen mix": ammoniac saltpeter, sugar, aluminum powder, and RDX). Such explosives have average density in the range 0.8-1.1 g/cm^3, which is close to that of common organic substances.
5. Improvised explosives that are made from widely available components (TATP, HMTD, etc.). Such explosives a) are cheap; b) have small minimal detonating mass (few grams); c) have average density 0.9-1.2 g/cm^3, like common organic substances; d) are instable and unpredictable, sometimes detonate spontaneously during storage; e) often are tightly packed (e.g. highly volatile TATP is usually sealed by paraffin to prevent evaporation and to prolong shelf life). Less volatile HMTD is sealed in a similar way to prevent its interaction with air moisture, which makes it too unstable; f) some IE (like TATP) do not contain nitrogen.

3. Detection of IE and IED

Detection of IED is complicated by the following factors.

- It is impossible to foresee in advance where the IED will be found. Since the suspected IED with unknown triggering mechanism cannot be touched, the detection and disposal equipment must be moved to the site. Thus, mobile equipment must be used to detect IEDs.
- The IED can be placed near the wall, in the corner or between some obstacles, so the detection systems should work with one-side access to the suspicious object.

- Environmental conditions where the IED is found are unpredictable, so the detection equipment must work both indoor and outdoor, in summer and in winter, etc.

One can split all IED detection techniques into three groups:

- Methods of detection of non-explosive components of IED (detonators, triggering mechanisms, metallic shells, electronic circuits, etc.)
- Methods of detection of vapors or traces of explosive substances (either standard of improvised).
- Methods of detection of bulk quantities of ES (the explosive charge itself).

4. Detection of Non-explosive Components of IED

Most common detection methods are:

- portable single-energy x-ray systems;
- nonlinear junction detectors (NLJD).

4.1. X-RAYS

Portable single-energy x-ray systems are used to determine the construction of the found IED. Advantages of such installations are:

- high penetrating ability (2-3 cm of steel);
- high spatial resolution (10-20μm), allowing detailed image of the IED.

However, such x-ray systems require access from two sides to the examined object, and they cannot distinguish between types of materials, and thus cannot distinguish between a real IED and a dummy.

4.2. NON-LINEAR JUNCTION DETECTORS

Non-Linear Junction Detectors (NLJD) are used to detect junctions between metals and/or semiconductors, which can be part of the IED triggering and control mechanism (see Figure 2). This method is:

- high speed (works in real time);
- standoff (detection range – tens of meters).

However, it does not distinguish between circuits that are part of the IED mechanism and those that are part of common electronic equipment (such as mobile phones), producing too many false alarms.

Figure 2. Non-linear junction detector NR900-K “Kite”.

5. Detection of Vapors and Traces of Explosives

Various explosives have different volatility. Volatility is characterized by the pressure of saturated vapors near the surface of the explosive, and is usually expressed as relative concentration of molecules of ES and molecules of air in the considered volume in e.g. particles per trillion (ppt).

Table 1. Vapor pressure for some explosives at 25°C.

	Nitroglycerine	TNT	PETN	RDX
Pressure, ppt	4.1×10^5 ppt	7.7×10^3 ppt	18 ppt	6.0 ppt

Table 1 lists vapor pressures fro some explosives at temperature 25°C. Modern equipment can detect vapors at levels of few or even fraction of ppt. However concentration of ES vapors inside the detection device is by many orders of magnitude lower than the pressure of saturated vapors on the ES surface. Vapor pressure drops if the IED is sealed (which is almost always the case) and additionally packed in a bag (frequently so). It can further drop at low temperatures (concentration of TNT vapors drop by a factor of two when temperature drops by 5°C, so at about 5-7°C detection of TNT vapors becomes problematic), or in presence of strong wind.

To increase vapor concentration inside the detection device special pre-concentrators are used, which pump through air and absorb ES molecules on special material.

Devices for vapor analysis can also be used to analyze traces of ES. In this case the surface of the suspicious object is wiped by a special napkin, which is then placed in the detection device, and molecules are carried to the detector by a stream of carrier gas.

Modern vapor detectors can reliable detect ES with vapor pressure in the range 10^5-10^6 ppt, for example, compounds based on nitroglycerine (dynamites). Detection of ES with vapor pressure in the range 10^3-10^5 ppt (e.g. TNT) is now at the limit of the existing equipment. Detection of ES with vapor pressure less than 10^3 ppt (RDX, PETN, C4) cannot be currently done without lengthy pre-concentration phase.

When vapor detectors are used to detect trace of ES, they can detect such traces at picogram level. RDX, PETN, C4 and most of other industrial and military ES can be found by these methods.

Vapor detection is currently done using biological, chemical and electrochemical sensors.

5.1. BIOLOGICAL SENSORS

The following biological sensors are currently used for ES detection:

- dogs
- rats
- bees
- antibodies.

Dogs and antibodies can work in large cities, while rats and bees are used for detection of land mines in countryside.

Dogs are capable of finding many industrially produced ES. E.g. US defense ministry trained dogs to detect nine types of explosives.

Techniques based on antibodies use specific property of some protein molecules to selectively react with certain substance, for example TNT. Antibodies are placed on the surface of a quartz crystal, which is a part of a microbalance system. When certain substance is present, antibodies join with its molecules and leave the surface of the crystal, and the resulting reduction of weight is measured by measuring frequency shift of the crystal. The technique is used for finding vapors of industrially produced military ES: TNT, PETN, and RDX.

The main advantage of biosensors is the significant practical experience of their application (dogs). The main disadvantage is the limited number of detected ES. While a very wide variety of both industrial and improvised explosives can be used in IEDs, dogs are typically trained to find only a limited number of ES. Applicability of antibodies to detection of IE has not been proved so far.

5.2. CHEMICAL AND ELECTROCHEMICAL METHODS

The following chemical and electrochemical methods are used for detection of vapors and traces of ES:

- ion drift spectroscopy;
- ion field spectrometry;
- mass-spectrometry;
- thermo-redox technology;
- gas chromatography.

In the ion drift spectroscopy method the air containing ES vapors is pumped into the device and ionized there by a source of beta-radiation. The ionized air then drifts in an external electric field to a collector. Lighter ions (for example, nitrogen and oxygen) have high mobility, therefore they quickly reach the collector; heavier ions (for example, molecules of ES) have smaller mobility and move to the collector longer. Thus, by measuring the drift time it is possible to distinguish between molecules with different mobility. Advantage of the method is its speed (measurements take few seconds), which allows one to use the device for real-time analysis. Disadvantage of the method is its low selectivity. Mobility of ions is not an individual characteristic of the substance, it depends in a complex way on mass, size, charge and other characteristics of the ion; therefore different substances might have similar ion mobility. As a result, such devices produce significant number of false alarms, some of them due to widespread domestic chemicals – gasoline, perfumes, oils, etc.

In the ion field spectrometry separation of ions is achieved by using a special filter consisting of two perpendicular electric fields. The obtained characteristic is the same as in the ion drift spectroscopy – mobility of ions – therefore both methods have similar advantages and disadvantages.

In the mass-spectrometry method ES vapors are detected by magnetic filtration of charged ions; the ions are identified by their charge-to-weight ratio. The method has very high selectivity, and can analyze both ES vapors and traces. However, mass-spectrometry devices include high-vacuum components, and are thus stationary installations. Recently, portable systems based on this method have been developed, but they are not specifically focused on detection of ES but are rather intended for general detection of dangerous organic substances in air, soil and water.

Thermo-redox (reduction-oxidation) technology is based on thermal decomposition of ES and subsequent reduction of NO_2 groups. The method is intended for detection of vapors, and is capable of determining presence of NO_2 molecules, which are part of most industrially produced ES. The

method cannot detect non-nitrogen ES (like TATP), and also can not distinguish ES from other chemical substances that contain NO_2 groups.

In the gas chromatography method the carrier gas containing vapors of ES moves inside a capillary, whose internal surface is covered by a sorbent. Different impurities reach the end of the capillary at different times depending on the relation between solubility of the impurity in the sorbent and in the carrier gas. Advantage of the method is its high selectivity, a wide number of detected ES (nitro ethers, TNT, PETN, RDX, etc.), and also the possibility to use it both for vapor and trace analysis. However, applicability of the method to the detection of improvised explosives has not been investigated so far.

The chemiluminescence method allows one to detect NO_2 groups, which are often part of explosives' molecules. The analyzed vapors are mixed up with ozone (O_3), and the chemical reaction is accompanied with the excitation of NO_2 molecules. Characteristic infra-red light emitted by these NO_2 molecules is then detected. Since this method cannot distinguish ES from other chemical substances containing NO_2 groups, it is often preceded by another device.

Electron capture detector can detect vapors of substances that strongly capture thermal electrons. Since many common substances (e.g. atmospheric oxygen, hydrocarbons etc.) also have the ability to capture electrons, the method is usually used in combination with some other technique.

In the surface acoustic wave method an output stream from a chromatographic column is blown over a special piezoelectric crystal, and vapors condense on the crystal's surface. The change of the resonant frequency of the crystal depends on the mass and elasticity of the condensed material.

The last three methods (chemiluminescence, electron capture, surface acoustic wave) can be regarded as different realizations of the gas chromatography method, and have the same advantages and disadvantages.

Methods of detection of ES vapors and traces possess the following important advantages:

- significant experience of using these methods (dogs, gas chromatography);
- high selectivity in some cases (e.g. for gas chromatography);
- a wide range of detected ES;
- methods can be used both to investigate objects and to examine people.

However, the following difficulties are associated with vapor and trace detection methods:

- Vapor detection can find only those ES that have high enough vapor pressure: (nitro ethers, TNT), while ES like RDX, PETN, C4 can be detected only by their traces left on the surface. Good quality packing may leave no detectable traces.
- IE like TATP and HMTD are often sealed, which makes detection of their vapors practically impossible.
- Some IEDs (such as igdanites) are difficult to detect even by trace detection, since their components like diesel fuel or nitric fertilizer are very widespread, and their traces can be found on many "innocent" objects.
- Vapor and trace detection methods cannot determine the mass of the explosive, and in many cases (e.g. strong wind) cannot determine even the location of the explosive.

6. Detection of Bulk Explosives

Direct detection of macroscopic quantities of ES is usually done by so-called active methods. The object is probed by some kind of penetrating radiation – radio waves, microwaves, X-rays, gamma-rays or neutrons – and ES are found by their characteristic response to the probing radiation.

One can mention the following groups of bulk explosives' detection methods:

1. x-ray methods;
2. electromagnetic methods;
3. "neutron in, gamma out" methods;
4. other nuclear and non-nuclear methods (neutron and gamma-radiography, acoustic, infra-red, etc.)

6.1. X-RAY METHODS

In x-ray systems the object is probed by x-rays with characteristic energy around 100 keV, and transmitted and/or reflected x-rays are detected.

X-ray methods produce very high-resolution images (1-20 μm) of the internal structure of the object. Sometimes, density and effective nuclear charge (Z_{eff}) of objects are also obtained.

The following variants of x-ray method are presently used:

- devices with single-energy transmitted x-rays;
- devices with two-energy x-rays;

- computer tomographs (CT);
- devices working on backscattered x-rays.

Modern single-energy x-ray devices can be made small and portable, however they can not determine either density or the effective charge of the inspected objects, and are not suitable for identification of ES. These devices are used only to visualize the internal mechanism of IEDs, as described above.

Two-energy x-ray devices provide both image and the effective charge of substances inside the inspected volume. Such devices allow one to divide all found substances into 3 groups: substances with small Z_{eff} (organics, explosives, etc.), substances with average Z_{eff}, and substances with large Z_{eff} (metals). A disadvantage of such devices is the need of two-side access to the inspected object.

X-ray computer tomographs allow one to obtain the image, effective nuclear charge, and density of substances. They also require access from several sides, so their use for detection of IEDs is very limited.

Backscattering x-ray systems provide effective nuclear charge of substances and can be used with one-side access to the object.

X-ray methods have following general advantages:

- High penetrating ability (2-3 cm of iron or 7-8 cm of aluminum).
- Very high-resolution images. (1-20μm).
- Some selectivity by effective nuclear charge (Z_{eff}) and density.
- Can be used both for objects and on people.

The major drawback of all x-ray methods is their inability to identify many commercially produced civil explosives and many IE used by terrorists (e.g. TATP, HMTD), since these ES have average densities in the range 0.8-1.2 g/cm^3, which coincides with the density range of most common organic materials organic substances and water.

6.2. ELECTROMAGNETIC METHODS

In electromagnetic methods the object is probed by electromagnetic waves with frequencies from fractions of MHz up to hundreds of GHz. The following groups of methods suitable for ES detection can be mentioned:

- magnetic resonance methods;
- quadruple resonance methods;
- subsurface radars.

In nuclear magnetic resonance (MR) methods the inspected object is placed into a strong homogeneous magnetic field and irradiated with probing electromagnetic radiation in the frequency range of several MHz. Transitions of atoms between discrete energy level in the external magnetic field absorb part of the energy of the probing wave. Frequencies of MR are specific enough for some chemical substances, and their measurements can be used for identification of ES. The method has the following disadvantages:

- MR devices are bulky and heavy, since a strong homogeneous magnetic field in large-enough volume must be created.
- Access to the object from several sides is needed (in many existing MR systems the sample is placed inside a magnetic coil).
- Strong external magnetic field can damage magnetic appliances.

Nuclear quadruple resonance (QR) method allows one to detect NO_2 groups, which are part of the majority of ES. The object is irradiated with pulsed probing electromagnetic radiation. If the frequency of the probing radiation coincides with the resonant frequency of the substances' molecules, the energy of the probing radiation is efficiently absorbed. After the probing radiation is switched off the molecules return to their initial state, emitting characteristic electromagnetic waves. Resonant frequencies of various nitrogen-containing substances lie in the range from 0.5 MHz to 6 MHz.

Advantages of the QR method are:

- Selectivity (QR frequencies for different chemical substances and for different ES are unique).
- Possibility to detect a wide variety of industrially produced military and civil ES (RDX, PETN and explosives made on their basis).
- Possibility to create systems with one-side access to the object.

Disadvantages of QRE are:

- Varying sensitivity to different types of ES (e.g. high sensitivity to RDX, low sensitivity to TNT).
- Existing QR systems are single-channel, i.e. during the tens of seconds-long measurement cycle only one type of ES can be detected. Thus, the total inspection time depends on the number of explosives to be found, and may be quite long.
- The method cannot detect non-nitrogen ES (e.g. TATP).
- Electromagnetic waves cannot penetrate even thin layers of metallic coating.

- Sensitivity of QR to IE is not currently known.

6.3. RADARS

Radars probe the inspected object with electromagnetic waves (e.g. microwaves), and the analysis of scattered waves allow one to obtain the image of the concealed object and to determine its dielectric characteristics.

Work on such radar, which uses continuous microwaves with stepped frequency change, is currently carried out at Radium institute[1]. This approach has some technical advantages over classical pulsed systems, and allows automatic identification of metallic and dielectric objects.

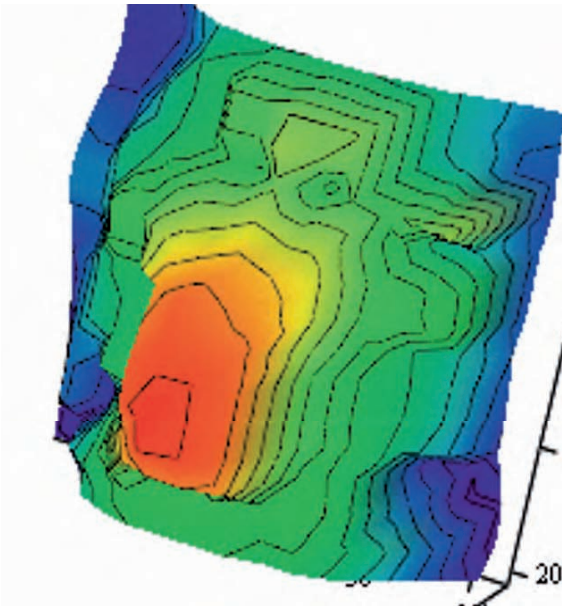

Figure 3. Example of an image by a microwave radar of explosives concealed under clothing on human body.

The method produces images of the concealed object with resolution 1-2 cm, works with one-side access, can be standoff and real-time. However, it cannot determine the type of the found explosive.

Electromagnetic methods are completely safe for objects and people. However, they cannot find explosives wrapped in metallic coating, but can detect presence of such coating, even if it is a very thin metallic film.

[1] See article by V. Averianov in this volume for more details.

6.4. TERAHERTZ

Recent advances in ultra-fast pulsed laser technology have led to generation and detection of broad bandwidth Terahertz (1 THz = 10^{12} Hz) radiation. Apart from producing very high-resolution images, terahertz systems can be selective, since many explosives have unique THz spectral properties when compared to the surrounding materials.

The main advantages of the terahertz technology is very high image resolution and selectivity to explosives. The main disadvantage is high attenuation in wet environments, so that even relatively thin layers of wet clothing or high air humidity can become a serious obstacle for terahertz-range electromagnetic waves.

6.5. "NEUTRON IN, GAMMA OUT" METHODS

The idea of "neutron in, gamma out" methods is to irradiate the inspected object with neutrons and to detect secondary gamma-radiation, which is produced in interactions between neutrons and nuclei of chemical elements constituting the object. Each chemical element is characterized by a unique "gamma-signature", so analysis of gamma-ray spectra yields chemical composition of the object.

The following features of chemical composition distinguish ES from non-explosives:

- Most ES contain oxygen, carbon and hydrogen.
- Overwhelming majority of ES contain nitrogen.
- Partial densities of oxygen, carbon and nitrogen in ES exceed those of non-explosive organic substances.
- Partial density of oxygen in ES is higher than that of carbon ($O > C$), which ensured the so-called oxygen balance condition needed for detonation.
- If ES contains nitrogen its partial density is not less 0.2 from that of oxygen ($O/N < 5$).

Figure 4 shows partial densities O/N and C/N for widespread explosives and common non-explosive materials.

Figure 5 shows partial density of carbon+oxygen versus partial density of oxygen for military explosives, non-nitrogen ES (TATP), common non-explosive materials and food.

One can see, that by measuring partial densities of carbon, oxygen and nitrogen one can distinguish between industrial and homemade explosives on one side and non-explosive substances on the other.

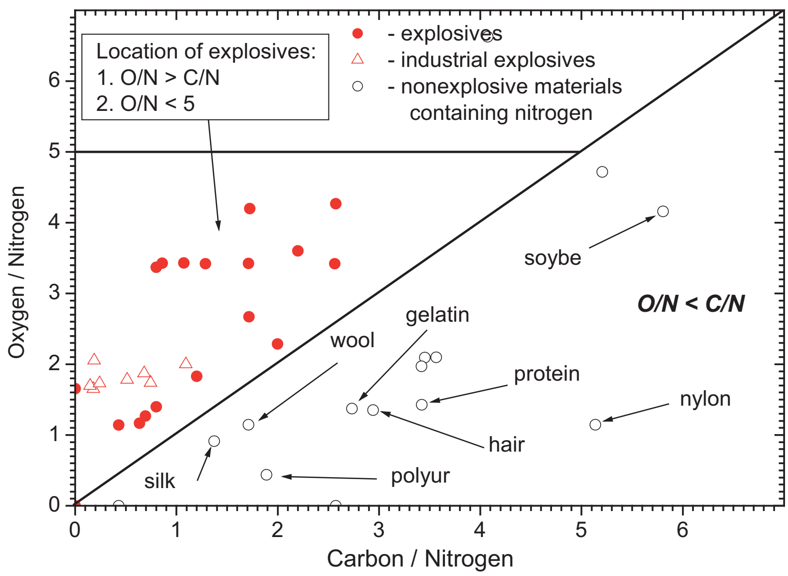

Figure 4. Ratios between partial densities of oxygen, carbon and nitrogen for military ES, civil ES, common non-explosive materials and food.

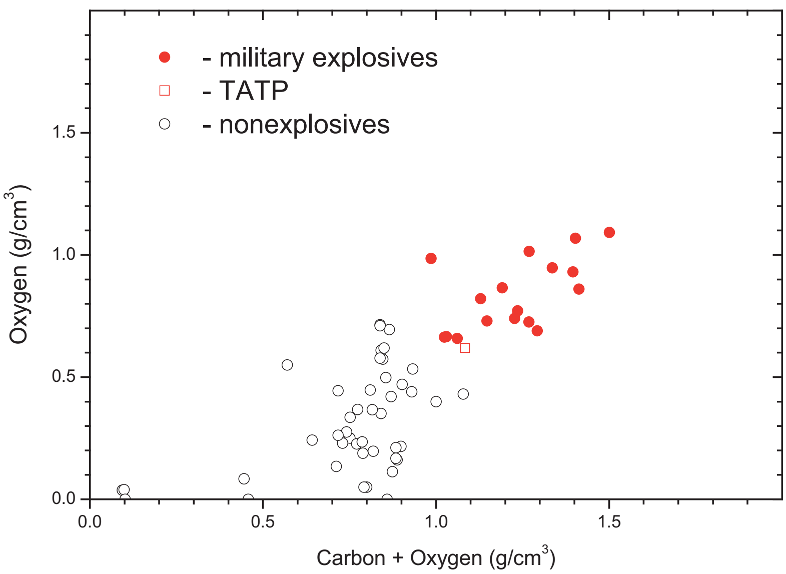

Figure 5. Partial density of carbon+oxygen versus partial density of oxygen for military explosives, non-nitrogen ES (TATP), common non-explosive materials and food.

At present the following “neutron in, gamma out” methods are used for detection of ES:

1. Thermal Neutron Analysis (TNA)
2. Fast Neutron Analysis (FNA)
3. Pulsed Fast Neutron Analysis (PFNA)
4. Pulsed Fast and Thermal Neutron Analysis (PFTNA)
5. Nanosecond Neutron Analysis/ Associated Particles Technique (NNA/APT).

6.5.1. *Thermal Neutron Analysis (TNA)*

In TNA the object is irradiated by slow (thermal) neutrons, which produce gamma-rays in reactions of radiative capture with the nuclei of chemical elements constituting ES. E.g. reactions with nitrogen produce 10.8 MeV gamma-rays, on hydrogen –2.23 MeV gamma-rays, on chlorine –7.50 MeV and 6.11 MeV gamma-rays, etc. Gamma-rays are then detected by gamma-detector.

Thermal neutrons cannot be produced directly; they are obtained by slowing down fast neutrons using hydrogen-containing thermalizer. Fast neutrons are produced either by spontaneous source or in a D-D neutron generator.

The main advantage of the method is its relative simplicity and one-side access.

The disadvantages of TNA are:

- It finds only ES containing nitrogen.
- It cannot distinguish nitrogen in ES from that in non-explosive substances (wool, leather etc), which leads to a large number of false alarms.
- A massive thermalizer is needed, increasing the weight and dimensions of the TNA device.

6.5.2. *Fast Neutron Analysis (FNA)*

In FNA the object is irradiated with a continuous flux of fast neutrons with energy above 8 MeV, which produce characteristic gamma-rays in inelastic scattering reactions with nuclei of carbon, oxygen and nitrogen (4.44 MeV gamma-rays for carbon, 6.13 MeV and other lines for oxygen, 5.1 MeV and other lines for nitrogen). Detection of these secondary gamma-rays provides information about relative concentrations of carbon, oxygen and nitrogen in molecules of the inspected substance.

Advantages of FNA method are:

- selectivity, since the method is sensitive to almost all elements constituting explosives;
- one-side access to the inspected object.

The main disadvantages are:

- The method does not have spatial resolution, so if there are two objects close to each other, it will give their average chemical composition, which is related in an unknown way to the chemical composition of ES. Thus, FNA is suitable only for inspection of large homogeneous objects.
- High level of gamma-ray background leads to the low effect/noise ratio and therefore to long measurement times.

6.5.3. *Pulsed Fast Neutron Analysis (PFNA)*

PFNA is similar to FNA, but uses pulsed neutron flux (with pulse duration of several nanoseconds) to irradiate the inspected object. This allows one to use time of flight information to determine the location of the ES inside the inspected volume. By using collimators for the neutron beam one can get a 3D distribution of carbon, oxygen and nitrogen in the investigated object.

Advantages of PFNA are:

- Highly informative and reliable method.
- Low level of gamma-background, since gamma-rays are measured only between the neutron pulses.

However, in order to have nanosecond neutron beams a PFNA device must use large particles accelerators, which are bulky and expensive.

6.5.4. *Pulsed Fast and Thermal Neutron Analysis (PFTNA)*

PFTNA is a combination FNA and TNA. The object is irradiated by a pulsed neutron flux (pulse duration tens of microseconds) from a D-T neutron generator equipped with a thermalizer. During the neutron pulse the system measures gamma-rays formed in inelastic scattering of 14 MeV neutrons on carbon and oxygen (FNA), and between neutron pulses – gamma-rays formed in capture reactions of thermalized neutrons with nuclei of nitrogen, hydrogen and chlorine. Thus, PFTNA is sensitive to a larger number of elements than FNA or TNA separately, which leads to its higher reliability.

Advantages of PFTNA are:

- High reliability and informativity.
- PFTNA device can be made mobile, since portable neutron generators with 10-20 μs pulses are produced commercially.
- Work with one-side access to the object.

However, like both TNA and FNA, PFTNA does not have spatial resolution and has rather low effect/noise ratio. In practice PFTNA has been only applied for detection of explosives and UXO in homogeneous environments.

6.5.5. *Nanosecond Neutron Analysis / Associated Particles Technique (NNA/APT)*

Nanosecond Neutron Analysis / Associated Particles Technique (NNA/APT) uses the fact, that in d(t,α)n reaction, which is used to produce fast neutrons in portable neutron generators, mono-energetic neutrons ($E \approx 14$ MeV) and alpha-particles ($E \approx 3$ MeV) are emitted simultaneously in opposite directions. If a position-sensitive alpha-particles detector is placed close to the target of the neutron generator, then each detected alpha-particle "tags" the corresponding neutron, so its time of emission and direction are known. All secondary gamma-rays, that are produced in inelastic scattering of fast neutrons on nuclei of carbon, oxygen, nitrogen, aluminum and many other light chemical elements, must reach the gamma-detector within very narrow (few nanoseconds) time intervals determined mostly by the time of flight of fast neutrons to the object. Background gamma-rays that are not correlated in time with "tagged" neutrons are rejected by the data acquisition system. Use of position sensitivity of the alpha-detector and time-of-flight analysis allow one to obtain three-dimensional spatial distribution of chemical elements in the examined object[2].

Figure 6. SENNA – portable sensor for explosives' detection based on Nanosecond Neutron Analysis.

[2] More details about NNA are given in the article by D. Vakhtin et al. in this volume.

Advantages of NNA/APT are:

- Very high reliability and selectivity, since the method is sensitive to all elements constituting ES, possesses spatial resolution, and allows one to obtain three-dimensional distributions of chemical elements in the examined volume.
- Portable devices can be created, since portable neutron generators with associated particle detectors are now commercially available.
- One-side access to the inspected object.

6.5.6. *General Advantages and Disadvantages of "Neutron in, Gamma out" Methods*

The important advantage of all "neutron in, gamma out" methods is their high penetrating ability and informativity. The main disadvantage is that they cannot be used for screening people.

7. Other Methods

Among other methods, that are not described in this article, one can mention metal detectors, gamma-ray and neutron backscattering and radiography, acoustic sensors, passive infra-red sensors and many other techniques, that are still to be evaluated for the task of detection of IE and IED.

8. Conclusions

Detection of IE and IED is a difficult task, because of a wide variety of explosive substances and triggering mechanisms that can be used by terrorists. Applicability of many existing methods to detection of IE has not been investigated.

In case of IED detection direct detection of bulk explosive charge is preferable compared to trace and vapor detection, since it provides immediate information about location of the explosive charge, and possibly type of the explosive and its mass estimation.

For inspection of people electromagnetic methods may be the best choice, since they work remotely and are safe for humans and electrical appliances.

Exact location, shape, mass and type of the explosive charge must be determined before disarming an IED. X-ray (and possible radar) images can be very useful in determining the degree of threat posed by an IED.

Vapor detectors are the most effective tools for conducting general monitoring of large areas over extended periods of time.

When suspicious objects are inspected, nuclear-based methods may provide the required information about chemical composition, location and mass of the explosive charge.

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ON-SITE ANALYSIS OF EXPLOSIVES IN VARIOUS MATRICES

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Abstract. Lawrence Livermore National Laboratory (LLNL) has developed several different strategies and technologies for the on-site detection of explosives. These on-site detection techniques include a colorimetric test, thin layer chromatography (TLC) kit and portable gas chromatography mass spectrometer (GC/MS).

Keywords: Trace explosives detection, on-site detection of explosives, colorimetric detection

1. Introduction

The screening of suspicious containers on-site and the search for trace explosive residue in a post-blast forensic investigation are of great importance. For these reasons, LLNL's Forensic Science Center has developed a variety of fieldable detection technologies to screen for a wide range of explosives in various matrices and scenarios. Ideally, what is needed is a fast, accurate, easy-to-use, pocket-size and inexpensive field screening test for explosives.

2. Colorimetric Approach

One technology that can achieve some of these requirements is the colorimetric detection kit for explosives. As a result, LLNL has been actively developing and improving a colorimetric test for explosives, the Easy Livermore Inspection Test for Explosives (ELITE) coupon. The ELITE coupon is designed with a removable swipe to collect the questioned sample, the swipe is then placed back into the coupon holder and a Meisenheimer complex reagent (ampoule #A) is broken. The solution then wicks across the swipe. The development of color indicates the possible presence of an explosive; if no color is produced, a Greiss Reagent (ampoule #B) is broken.

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H. Schubert and A. Kuznetsov (eds.), Detection and Disposal of Improvised Explosives, 27–32.

If a color develops then, it indicates the possible presence of an explosive (Figure 1).

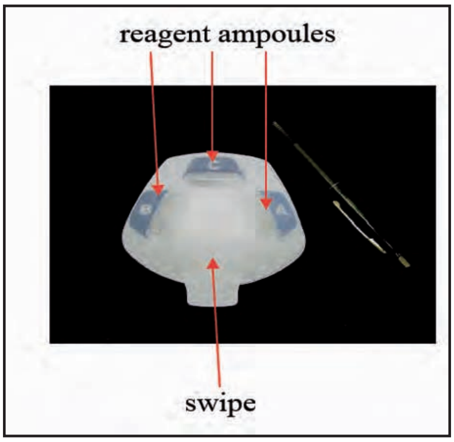

Figure 1. ELITE Coupon: Removable swipe, Meisenheimer complex regaent (ampoule #A), Greiss Reagent (ampoule #B) and other potential explosive indicators (ampoule #C).

The LLNL ELITE Coupon has been tested against a variety of common explosives at LLNL (uncertified tests), and the results are very promising (refer to Table 1).

In addition, the ELITE kit was evaluated in a field test to asses its performance under real world environmental conditions. An out of service limousine was used as the test item and several improvised devices containing varying amounts of ANFO (ammonium nitrate and fuel oil) were placed in the driver door, trunk and rear seat. Swipes taken pre and post blast (inside and outside limousine) were evaluated by ELITE. The ELITE was effective both pre-and post-blast in detecting the explosive; even the bomb technician hands tested positive after preparing and handing the improvised devices.

3. Thin Layer Chromatography (TLC) Kit Approach

In some situations there is a need to rapidly analyze a large number of samples in the field for the presence of explosives. For this scenario, TLC is an ideal technology. It is a sensitive technique that makes use of the migration of compounds within a solvent and coated TLC plate to obtain the separation of complex mixtures (both unknowns and explosives reference standards) for

Table 1. Summary of explosives detected and their minimum quantities utilizing the ELITE coupon chemistry. The "a" on the chart represents explosives detected by the Meisenheimer complex and "b" for explosives producing a color with the Greiss Reagent.

Explosive	Color & DL (ng)	Explosive	Color & DL (ng)
TNT	a 100	1,2-Dinitroglycerin	b 500
2,4-Dinitrotoluene	a 200	1,3-Dinitroglycerin	b 500
2,6-Dinitrotoluene	b 1000	RDX	b 100
2-Amino-4,6-dinitrotoluene	a 1000	HMX	b 100
4-Amino-2,6-dinitrotoluene	a 2000	Dinitroethylene glycol	b 100
Nitroglycerin	b 100	1,2,4-Butanetriol trinitrate	b 100
4-Nitrotoluene	b 5000	1,2,4-Butanetriol-1,4-dinitrate	b 100
Tetryl	a 100	1,2-Propanediol dinitrate	b 100
1,3,5-Trinitrobenzene	a 50	Nitrocellulose	b 100
1,3-Dinitrobenzene	b 200	1-Mononitroglycerin	b 1000
1,2-Dinitrobenzene	b 200	2-Mononitroglycerin	b 1000
PETN	b 100	Sodium Nitrate	b 5000
		Potassium Nitrate	b 5000
		TATB	b 5000

Figure 2. Out-of-service limousine utilized for testing the ELITE kit with improvised explosives devices containing ANFO (ammonium nitrate and fuel oil).

explosives identification. After the compounds have migrated on the TLC plate, color reagents are sprayed onto the plates to highlight target compounds, Figure 3. With a basis of classic TLC, LLNL has modernized the technique by incorporating digital technology into the kit. For example, a digital camera/light box takes an image of the processed TLC plate, the image is transferred to a lap top computer and a software program compares the migrations time of the reference materials (explosives standards) and the

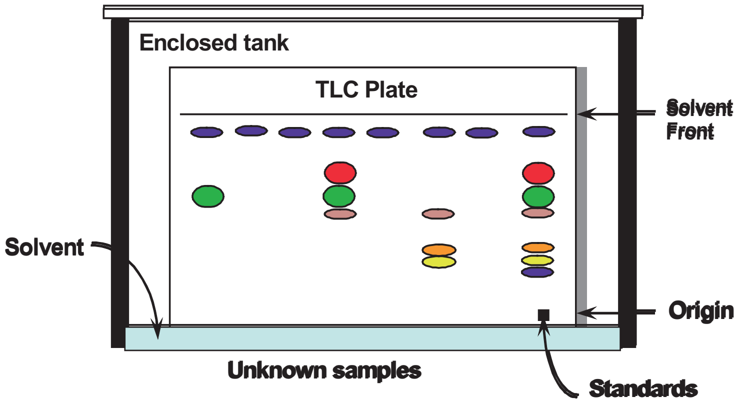

Figure 3. Protocol that makes use of the migration of compounds with a solvent and coated TLC plate to obtain the separation of complex mixtures.

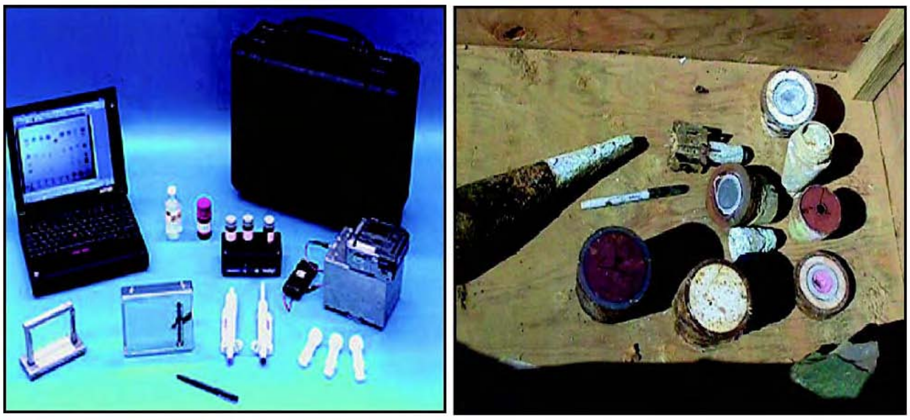

Figure 4. LLNL TLC kit (right) and unearthed munitions screened for explosives utilizing the LLNL TLC kit.

associated colors with the analyte "spots'. This LLNL TLC kit has been evaluated in field deployments (Figure 4).

4. Portable Gas Chromatography/Mass Spectrometer (GC/MS) Approach

One technology that can achieve greater specificity and detect a wider range of threat materials is a portable GC/MS system. LLNL and other research groups have been developing various portable GC/MS instruments for several years. LLNL, however, has developed a fully functional, laboratory-performance-based system that can be deployed to field locations for analysis of complex organic samples. The LLNL system incorporated an Agilent quadrupole mass

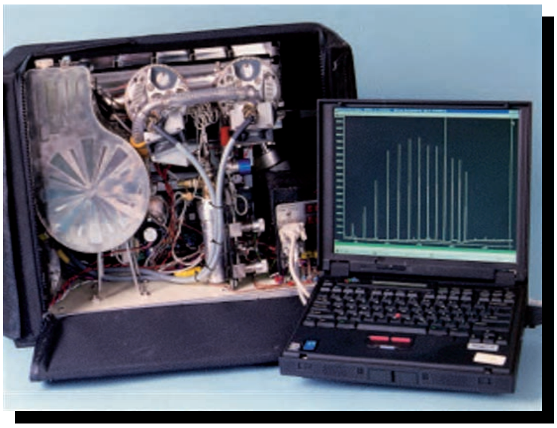

Figure 5. LLNL portable GC/MS system; weight approximately 70 pounds.

Figure 6. Vehicle loaded with explosives (ANFO) and PETN detonation cord; swipes analyzed by LLNL portable GC/MS system confirmed the presence of PETN and fuel oil.

analyzer, light weight vacuum chamber, on-board carrier gas system, and unique gas chromatography oven (25-310^{o}C), Figure 5. The portable GC/MS has been deployed to various areas for evaluation and in one instance it was deployed to a bomb evidence training site to collect and analyze swipes pre- and post-loading of explosives into the vehicle. The portable GC/MS was able to successfully identify PETN (detonation cord utilized for the ANFO device) in the post loaded vehicle, Figure 6.

5. Summary of Detection Approaches

The selection of a particular on-site analytical detection technique for explosives must be systematically evaluated for possible unforeseen user scenarios. For example, the effects of humidity, heat, and cold or high levels

of environmental chemical background may impede the detection technology or even render it ineffective. For this reason, it is advantageous to utilize serval detection systems. Below are summarized advantages of utilizing a suite of explosive detection technologies developed by the LLNL FSC:

Colorimetric Test for Explosives (ELITE)

- Rapid screen for explosives in the field
- Requires less than 2 minutes per analysis
- Kit weight less than 5 lbs.
- Nano-gram detection limit for most explosives
- To date: Detects 26 explosives
- New ELITE coupon, less expensive and lightweight

Thin Layer Chromatography (TLC)

- Rapid analysis of a large number of samples
- Easy to use, low cost
- Requires 25 minutes for 10 samples
- New reagents needed, smaller kits
- Nano-gram detection for most explosives
- To date: detects 25 explosives

Portable GC/MS

- Identification of questioned samples in the field
- 25 minutes per analysis
- Requires extensive training
- Higher maintenance costs
- External power (generator)

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1) Lawrence Livermore National Laboratory, Science and Technology Review, Forensic Science Center, April 2002 page 11-18.

This work was preformed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

IEDS DETECTION BY EXISTING DETECTION TECHNIQUES

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1. Introduction

The experience obtained in the fight with terrorist attacks by explosives in the last period proved, that the terrorist tools and operational systems of bomb attacks have developed very quickly. New forms of bomb attacks are more sophisticated, more dangerous, effective countermeasures complicated and in some case not adequate.

The broad use of remote control of IED initiation by mobile phones gives to terrorists the choice of exact moment to start the bomb attack and also the possibility to initiate the bomb immediately, in suspicion, that security officers discovered the bomb.

Therefore, the detection systems, having reliable detection efficiency in broad range of IEDs used, are a big problem and the effective response to terrorist bomb activities is a permanent important task.

The aim of this paper is to analyse the efficiency of existing detection techniques and factors, which influence the detection. IEDs design and explosives used are characterised.

The risk of demilitarised explosives and insufficient legislation concerning transfer, reworking and use of these products is discussed and some recommendation presented.

2. Main Detection Systems

Important task in screening operations is covered by the visualisation of the checked object content by X-rays or other imaging techniques. In fact X-ray equipment is the most frequently used tool for detection of hidden IEDs in stabile checking points, the visualisation enables also the search of further contraband as weapons, and narcotics.

Electronic detectors of explosives are further effective tools for detection of explosive components of IEDs by analysing vapours and/or particles of these compounds.The very important way of IEDs detection is the use of special trained dogs. The sensitivity of the dog nose is unique and electronic detectors have not yet overcome the dog detection ability.

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It was found, that simultaneous use of several systems should give some substantial synergy of the detection efficiency, typical example is integration of X-ray and electronic detectors at stabile checking points in airports, other transport terminals and important buildings.

Multi-sensor approach, progress in micro and nano technologies will open the way to future improvement and increase of sensitivity especially in the field of electronic detectors.

3. Factors Influencing the Detection Efficiency

Many factors are influencing the practical detection ability. Very important are characteristics of screened object, such as dimensions of the object, properties of the objects envelope (material of walls or packing). The detection of IEDs is influenced also by the content of checked object and by properties of individual items. The access to the screened object and into the object is also important.

The efficiency of detection is very dependent on the IED design and explosive used. The detection activities are performed in very different scenarios, which are also a substantial factor influencing the detection procedure. In some circumstances, the decisive role has the time factor, i.e. time period, which is at disposal for detection.

4. IED Design

IED design offers a broad range of possibilities, from mechanical alarm-clock, battery and stick of dynamite to sophisticated initiation train and explosive charge masked as innocent component of checked object. Important aspect is the mass of explosive used. The range of explosive mass used in IEDs should be very different, starting with several grams in letter bombs and ending with the mass of several tons of explosive in a lorry on the other end of this range. There are many types of explosives used in IEDs and many possible designs, differing in initiation chain, starting mechanism and packing arrangement. There are also many different scenarios in which IEDs are used. The main areas of bomb attacks are transport means and transport ways, including air transport, railway, sea and river transport, roads, important buildings, hotels, theatres, sport halls and other places with high concentration of citizens.

The IED can be hidden in uncountable number of objects starting with standard piece of luggage and ending with a body of dead dog laying at the road.

Very dangerous are mobile or radio controlled IEDs situated in transport means, on roads, streets and places with high concentration of people.

Extremely dangerous are:

- IEDs fixed on bodies or carried in personal luggage of suicide bombers
- IEDs in cars containing big amount of explosives or ammunition

The effective detection and adequate countermeasure is in this case very difficult.

5. Explosives Used in IEDs

There are several main groups of explosives, which have been used in IEDs.

5.1 MILITARY EXPLOSIVES

The range of military explosives is very broad, but most of explosives are mixtures of basic explosive compound, number of which is not very high.

Basic explosives are as follows:

TNT, PETN, RDX, HMX, NG, NC

Most of military explosives, including explosive charges in ammunition, plastic explosives, smokeless powders and rocket propellants are mixtures of basic explosives with inert ingredients or mixtures of several basic explosives with further ingredients.

Therefore, the detection of military explosives is oriented on basic explosives. This is true when electronic detectors are used, or when the explosives detection is performed by gaining the typical spectra evolved by radiation methods.

5.2 DEMILITARISED EXPLOSIVES

This group of explosives is in principle identical in chemical composition with military explosives. The detection methods using detection by spectra typical for individual explosive compound are identical with the detection of military explosives.

When imaging technologies without identification step by spectra are used, the detection procedure should be rather complicated, as physical form of ammunition and also of explosive and propellant components is often substantially changed in the process of dismantling of ammunition and reworking of explosive components. Demilitarised explosives are often not well-defined products. Then, the detection of such product, only by imaging technologies, should be rather ineffective.

5.3 INDUSTRIAL EXPLOSIVES

Industrial or civil explosives are explosives used in civil applications, mainly in blasting technologies.

The basic categories should be specified as dynamites, ammonites, ANFO, slurries, emulsions and black powder.

The detection of dynamites is based on NG. Taking into account the relatively high content of NG in dynamites and the high vapour pressure of this compound, the detection of dynamites is easy.

Ammonites, which contain TNT should be detected by detection of this explosive component. DNT, which is usually present in dynamites, have a high vapour pressure and therefore, can be easily detected by electronic detectors.

Slurries, emulsions and ANFO usually did not contain any explosive component. All these products have in their composition substantial amount of Ammonium Nitrate (AN). Therefore, the detection of these products should be oriented on AN, which has relatively high vapour pressure. The problem consists in the fact, that traces of AN, and of other inorganic nitrates are often present in surroundings and the probability of false alarms is rather high.

5.4 IMPROVISED EXPLOSIVES

The exact definition of this group of explosives is not quite clear. We can assume, that also explosive compounds used in army and civil explosives, but prepared by improvised procedures by unauthorised subjects can be counted in this group.

Some improvised explosives represent specific chemical compounds prepared by unauthorised subjects for criminal/terrorist purposes.

Main representatives of this group are:

- Organic peroxides, from which TATP (Triacetonetriperoxide) is often used
- Ammonium Nitrate – fuel (oil, kerosene, sugar, flour) mixtures

Other, rather exotic compounds can be also used (Urea Nitrate, mixtures of chlorates and perchlorates with fuel, primary explosives)

Most of improvised explosives can be detected by the same technologies used in the detection of military and civil explosives.

6. Detection Ability of Detection Systems

6.1 ELECTRONIC DETECTORS

Electronic detectors based on IMS and GC are able to detect, by analysing vapours and/or particles, most of military and civil explosives and also TATP, the frequently used improvised explosive. The sensitivity of this equipment is fully sufficient in particle detection, collection of 1 particle usually enables the positive result.

The big group of civil and improvised explosives contains as main component Ammonium Nitrate. The detection of this compound should be a problem taking into account the fact, that AN is present in low concentration in many places and probability of false alarms is high.

The vapour detection is dependent on conditions at detection, from which most important are: vapour pressure of explosive, barrier properties of packing, temperature, sampled air quantity. In unfavourable conditions, the vapour detection is not fully reliable method.

Therefore, the systems using simultaneously vapour and particle detection are very effective. The detection efficiency is increased by pre-concentration of explosive traces from sampled air, some equipment is able to work with pre-concentration factor as high as 100 000. Such high pre-concentration factor is typical for stabile screening systems.

6.2 DOG

The dog remains the unique tool for trace detection. The sensitivity of dog nose is higher than we can see at the best electronic detectors. This is the reason, why the dog is able to detect explosives even at low temperatures at which most detectors are not fully effective. In fact, we have not quite exact knowledge about the mechanism of dog sniffing, but this is not decisive for practical application.

Dogs have their place in search for hidden IEDs in various scenarios and the efficiency of dogs has been confirmed by steady rise of dog numbers used in security missions.

6.3 COLOUR REACTIONS

Explosives produce colour reactions with specific reactants, and this knowledge has been exploited in trace detection. The sensitivity of this detection method is lower in comparison with electronic detectors, but when we are able to collect several particles of explosives, the detection is

reliable. Usually, collection of 1 average particle is sufficient for positive detection.

The advantage of explosive detection by colour reactions is a simple and easy procedure, low price of detection set and very short time necessary for training of personal. Detection sets for colour reaction can detect also AN, chlorates and perchlorates, it means important components of some civil and improvised explosives.

6.4 IMAGING AND RADIATION TECHNOLOGIES

X-ray systems are broadly used as the basic screening tool for control of luggage, postal sending and further objects. The substantial progress of X-ray technology in the last period enables the better imaging of the object content, 3 dimensional search of the interior and some systems can identify the chemical compounds present in suspicious part of object by angle diffraction spectrum. Diffraction spectrum substantially increases the possibility of detection and identification of explosive charge in checked objects.

Further radiation and wave technologies as neutron in - gamma out detection, LIBS spectroscopy, radar, NMR, QMR and other wave systems are in development phase and/or field testing and substantial progress is to be expected in near future.

6.5 DETECTION OF MARKING AGENTS IN PLASTIC EXPLOSIVES

Practical importance among marking agents, specified in the Technical Annex of Montreal Convention on the Marking of Plastic Explosives for the Purpose of Detection, have the following compounds:

- 2,3-Dimethyl-2,3-dinitrobutane (DMNB)
- para-Mononitritoluene (p-MNT).

Vapour detection of DMNB, the most popular marking agent for plastic explosives, by IMS is not very effective. The reason is, that cluster ions formed from molecules of DMNB by irradiation have the low thermal stability and therefore, the yield obtained after acceleration in drifting tube is low.

On the other side, the detection of DMNB by GC is excellent.

In fact most detectors used in detection practice at this time are based on IMS. The reason is advantages of IMS in comparison with GC such as lower price, lower weight, absence of carrying gas, and a very short time of analysis.

This discrepancy is to be solved by some acceptable way, but the solution will be not easy.

7. Efficiency of Existing Detection Systems in Different Applications

7.1 DETECTION OF IEDS ON STABILE CHECKING POINTS

The integration of X-ray imaging and electronic detectors should be considered as an effective detection tool for most IEDs. The imaging ability of x-ray systems is high and combination of vapour and particles detection is the very effective procedure in detection of traces of explosives on persons, luggage and other objects. Further gradual improvement of both methods is supposed including the application of fully automatic detection equipment.

Imaging radiation systems enabling to gain spectra characteristic for individual explosive compounds should substantially increase the detection and explosive identification ability.

The efficiency of up-to-date stabile detection systems is high and also the deterrence effect is important.

7.2 DETECTION OF IEDS BY MOBILE SYSTEMS

Mobile systems are used for search in various areas, in which some IED should be presence.

A portable electronic detector, mobile x-ray equipment, dogs and colour reactions are the main mobile detection tools.

Important role in some scenarios should play detector of electronic components of detonators and other components of initiation train controlled by initiation command from mobile phones or radio (Eagle Locator used in Russia).

Synergy of simultaneous use of several detection systems is the way for improvement the detection results. Efficiency of mobile systems is in many applications high, but in some conditions is not adequate. These unfavourable conditions are low temperature, strong wind and rain and also barriers, which complicate the access to the checked object.

7.3 STAND-OFF DETECTION OF IEDS

Extremely difficult problem, which emerged in the last period is the massive use of IEDs controlled on distance by radio or mobile phone and attacks by bombs fixed oh the body of suicide bombers.

Also attacks by cars filled by big amount of explosives present high danger and consequences of such attacks are very heavy.

The experience from Iraq, Chechnya and other countries proved, that the detection of these terrorist tools on distance and effective countermeasures is a very uneasy task.

Unfortunately, no effective, service ready technology for stand-off detection is at disposal. Therefore, research and development of effective detection technology for stand-off detection should have the highest priority.

Also quick and effective countermeasures able to counter such IEDs present a strong appeal to further research and development.

The progress in LIBS, MW and Radar technologies should lead to relevant methods in the near future.

8. Implications Deduced from Experience Gained in Last Period

The high frequency of remote controlled bomb attacks leads to the assumption, that any screening operation should be accompanied by jamming of relevant range of radio waves in area of screening to exclude the possibility of triggering of bomb by terrorist just during the screening. This is not quite new countermeasure, but the question is to be considered, if it is applied in all reliable situations.

Reliability of jamming of screening area at the stabile checking points in airports, sensitive buildings and other relevant places should be considered. Also, the fact that most screening operations are performed quite open, often in presence of many people represent some risk. The discreet screening should be an effective way, how to decrease the risk to start the bomb attacks during the screening operation.

9. Specific Risk of Demilitarised Explosives and Ammunition

It seems, that demilitarised explosives present some specific risk of criminal or terrorist misuse. There are more factors leading to this assumption. The legislative regulations controlling the demilitarisation process in most countries are rather weak

Properties and physical form of ammunition components including explosives are changing during the demilitarisation and products evolved from this process and further reworking have no exact specification.

The administrative and physical control of the demilitarisation process, reworking, transport and use of explosive components is not sufficient.

This situation can be demonstrated on the export of unmarked plastic explosive sprangdeg m/46 from Sweden to the Czech Republic

In the beginning, the Swedish army transferred 700t of plastic explosive sprangdeg m/46 to a company in Sweden and paid for the demilitarisation of the product. This company exported plastic explosive in original packing to the Czech Republic and this product was declared as phlegmatised PETN in transport documentation.

The export started in the beginning of 2004 and after 350t of explosive crossed the border of the Czech Republic, Czech custom officers at the border control discovered the real content of shipment. The shipment was stopped and 350t of Swedish plastic explosive was confiscated by Czech police and deposited in the store of Czech army.

This event has been investigated as criminal act and will come to court probably till the end of 2005.

10. Assumption

Different regulations valid in various countries, concerning the liquidation of ammunition, reworking and use of demilitarised explosives, support the transfer of huge quantities of these products from country to country often with changed properties and without sufficient specification.

Demilitarisation of big amount of ammunition should requires relevant, strict and effective regulations, which will make this process transparent giving at the same time the necessary information to states, in which the demilitarised components should be transferred as the subject of business activities.

Unfortunately some European countries did not ratified the Montreal Convention on the Marking of Plastic Explosives for the Purpose of Detection. Therefore, the transfer of unmarked plastic explosives among European countries is not under effective control.

ARW should consider making a recommendation to relevant national and/or international European institutions to prepare better regulation of demilitarisation process. Such regulation should lead to strict and effective control over possession, transfer and use of demilitarised explosives.

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MICROWAVE SYSTEM FOR INSPECTION OF LUGGAGE AND PEOPLE

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Abstract. Devices for standoff detection of explosives hidden on human body and in luggage based on gigahertz-range electromagnetic waves are described.

1. Introduction

Standoff detection of explosives concealed under clothing on human body cannot be done by existing methods. Any such detection system should fulfill the following main requirements:

- Work from distance of several meters (ideally, tens of meters) to provide early warning about the potential threat.
- Work secretly, so that the inspected person would not know he is inspected.
- Inspect moving targets.
- Be safe to public and cause no interference with cell phones etc.

Electromagnetic (EM) waves with frequencies about tens of gigahertz may be primary candidates for such detection system for the following reasons:

- They have high-enough penetrating ability in wet environments (unlike terahertz), enough to penetrate tens of meters of humid air and layers of wet clothing.
- They do not require bulky portals, which would de-mask the detection.

H. Schubert and A. Kuznetsov (eds.), Detection and Disposal of Improvised Explosives, 43–50.

- Very low power levels needed for detection are completely safe for health and electrical appliances.
- They provide images with high-enough resolution (~1 cm), which is enough to recognize the concealed threat while not presenting privacy problems (unlike, e.g. x-rays or terahertz).

2. Detection Method

The proposed system is based on an experimentally proven concept of a system for discreet remote inspection of persons by active probing with microwaves. The system is intended for real-time detection of metallic and dielectric objects hidden under clothes on body of a moving person.

Human body is a perfect reflector of gigahertz-range microwaves, so any object attached to it will be seen as having one or several additional reflecting surfaces. Metals and other conductors have only one (front) reflecting surface, while dielectrics have two (air-dielectric and dielectric-body). By exploiting this property, the detection system can provide the following information about the inspected target:

1. 3D image of objects hidden on human body.
2. Classification of detected objects into metals/dielectrics.
3. The value of dielectric constant of the object (if a dielectric).
4. The equivalent mass of the object.

Though not a unique characteristic of explosives, dielectric constant is an important additional indicator, which allows one to distinguish between concealed explosives and, say, a wallet containing plastic, paper etc.

3. Examination of Luggage

First experiments were carried out with luggage moving on a conveyor belt. The system can be used as an independent inspection tool, inexpensive and real-time, or as an additional sensor in conjunction with an x-ray and/or QR systems. Unlike both x-rays and QR, microwave system can visualize very thin metallic foils, which may be used to cover the explosives to make it undetectable by QR method. It can also provide dielectric properties and dimensions of objects inside suitcases, which can be used to facilitate detection with x-rays (e.g. to move from surface densities to volume densities).

Work of the system is based on irradiation of the examined luggage by microwave radiation, detection of transmitted and reflected electromagnetic field, and reconstruction of the 3D image.

The device consists of several (from 2 up to 4) linear antenna arrays located in the form of a portal, through which the conveyor belt passes. The EM field scatter from the luggage moving with constant speed is measured in a wide frequency band during the time sufficient for synthesizing the aperture in horizontal direction. The measured data are digitized and processed to obtain a three-dimensional image.

The above conceptual scheme was implemented in an experimental device working in frequency range 2-8 GHz. In the horizontal direction the aperture was synthesized due to the movement of the examined luggage, and in vertical – by moving the emitting and receiving antennae.

Prior to the experiments, dielectric properties of several types of real explosives were measured in the controlled environment.

The inspected suitcase contained many common objects (Figure 1) like clothing, magazines, photo camera, a pack of wax (imitating explosives), etc. Examples of the obtained images of the suitcase are shown at Figures 2 - 4.

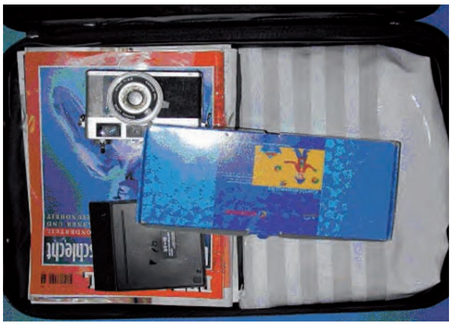

Figure 1. Contents of the inspected suitcase.

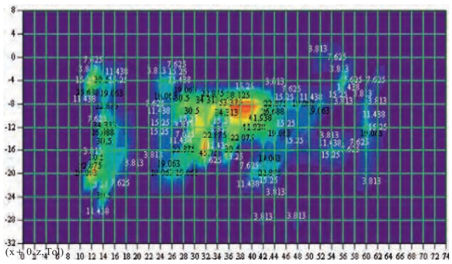

Figure 3. Distribution of thickness of dielectric in the suitcase assuming ε = 3.

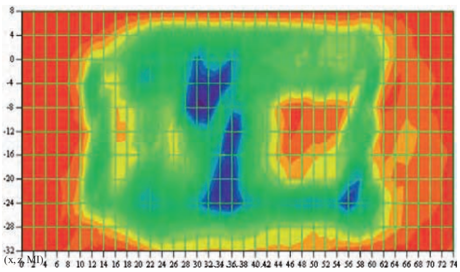

Figure 2. Transmission coefficient for different locations of the suitcase.

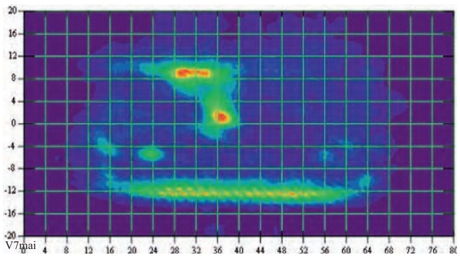

Figure 4. Cross-section of the suitcase: on the bottom – metallic frame; on top – photo camera; in the middle – battery.

Figure 2 shows transmission coefficient for the whole suitcase. Figure 3 shows distribution of dielectric thickness across the suitcase (in millimeters), assuming that dielectric constant is $\varepsilon = 3$. This allows one to estimate the amount of the potentially hazardous material. Figure 4 shows one of the cross-sections of the suitcase, on which metallic construction frame, photo camera and a battery are visible.

These figures provide one with the following information:

- detect unshielded dielectrics and determine their thickness;
- construct 3D image of the suitcase and determine dimensions and dielectric properties if its filling;
- detect any metallic objects inside the suitcase, regardless of their thickness, and determine the size of the shielded volume.

4. Detection of Explosives on Human Body

4.1. CHARACTERISTICS

Features of interaction of microwave electromagnetic radiation with matter allow one to solve the following tasks:

- detect and localize objects hidden under clothing of human body;
- divide the found objects into conductors/dielectrics;
- determine dimensions of hidden objects and equivalent weight of explosive;
- determine dielectric constant of found objects;

The proposed system for standoff inspection of people works on the principle of active probing with coherent radiation with stepped frequency change. The system consists of at least one matrix of elementary emitting and receiving antennae, electronics and the processing computer.

4.1.1. *Detection Limit*

Use of the antennae array with aperture of 1 m × 1 m and frequency range of 15 GHz allows one to receive at distance ~2 m the image of objects concealed under clothing on human body with spatial resolution of the order of 2 cm × 2 cm in-plane and 1 cm in-depth. Such resolution is enough to recognize threat objects like a handgun or a small explosive charge.

4.1.2. *Secrecy of Inspection*

The main unmasking element of the inspection system is the matrix antenna. The antenna can be made "flat" with dimensions as small as 1 m × 1 m × 0.1 m., and it can be covered from the front side by any dielectric material: plastic, cardboard, marble, granite etc. Thus, the device can be made look like a panel mounted on the wall, under floor, on the ceiling, in the elevator, and disguised e.g. as an information or an advertising board.

4.1.3. *Safety*

The power of the emitted EM radiation is determined by the distance, quality of the electronic channels, etc. Since no real focusing or EM waves is used, the density of the probing energy can be made very small – much smaller that that of a usual mobile phone.

4.1.4. *External Electromagnetic Background*

The system emits probing EM waves as a discrete set of very narrow frequency lines, which may be chosen not to interfere with other electrical appliances. On the other hand, these narrow frequency lines guarantee, that any interference from external sources can be easily filtered out.

4.2. EXPERIMENTAL RESULTS

The laboratory prototype of the inspection system was working in the frequency range 2-8 GHz and emitted coherent microwaves with frequency step dF = 125 MHz. The radiating aperture was synthesized by moving the elementary antenna with uniform step of 2 cm along vertical and horizontal axes within the rectangle with dimensions 60 cm × 40 cm. A 3D image was produced using digital focusing.

Figure 5. Laboratory prototype of the system for detection of explosives concealed on human body.

The laboratory prototype for detection of explosives concealed on human body is shown on Figure 5. The rectangle on the left photo indicates the boundaries of the inspected region.

A block of wax (yellow object on Figure 5) attached to the body simulated the explosive charge. Dielectric properties of wax are close enough to those of standard explosives. Another set of measurements was carried out for the case when the same block of wax was wrapped into metallic foil.

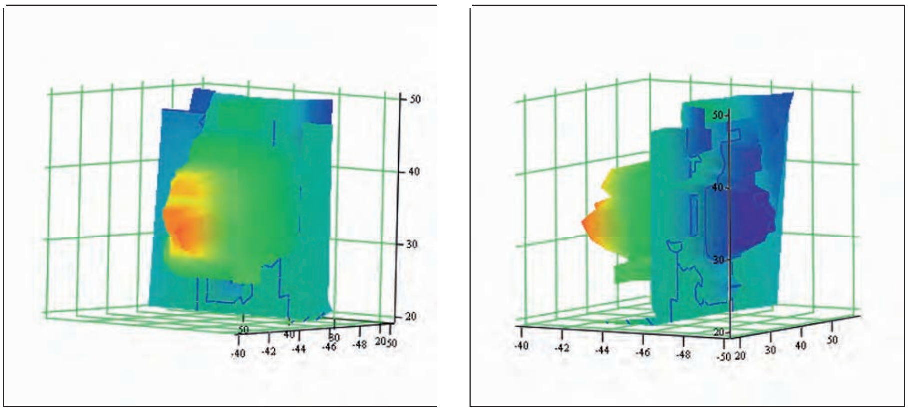

Figure 6. 3D image of the wax block attached to human body shown from two viewpoints.

A 3D image of the wax attached to human body (without metallic wrap) from two viewpoints is shown on Figure 6. Since the wax simulator, as well as the majority of explosives, is a dielectric, its image has two surfaces: the first surface is the front border air-simulator, the second – the border simulator-body, which is located from the front border at distance, determined by the electrical length of the simulator. Analysis of Figure 6 yields the following conclusions about the found object:

- The object attached to human body is a dielectric.
- Dielectric constant of the object is 2.6 (correct for wax; for some standard explosives the value of the dielectric constant was measured to be about 3).
- Equivalent mass of explosive corresponding to the detected object is 1.8 kg.

Figure 7 shows images of wax wrapped into metallic foil. Since metal, as well as human body, are reflectors of EM waves, only the first (front) border air-simulator is observed. Analysis of images on Figure 7 allows one to make the following conclusions:

- The detected object is a conductor.
- The equivalent mass of the explosive corresponding to the detected object is 2.2 kg. This value is higher than what was determined for the unwrapped wax, since in the latter case the density correction (determined from dielectric permeability) cannot be applied.

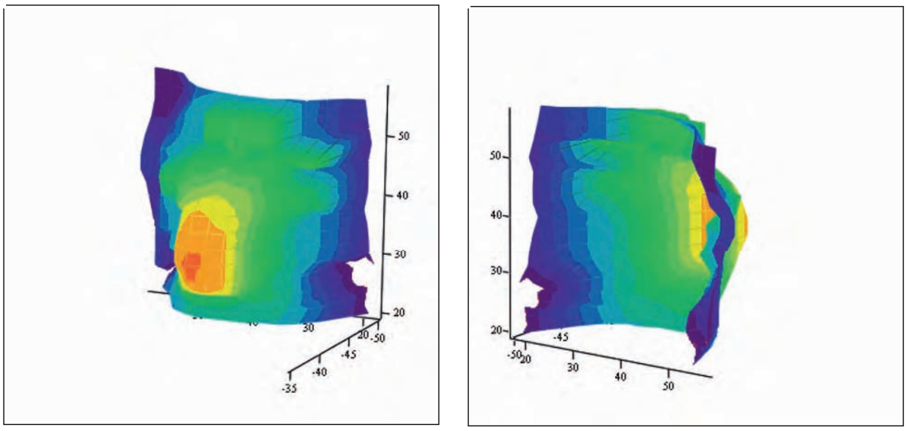

Figure 7. 3D image of the wax wrapped into metallic foil attached to human body shown from two viewpoints.

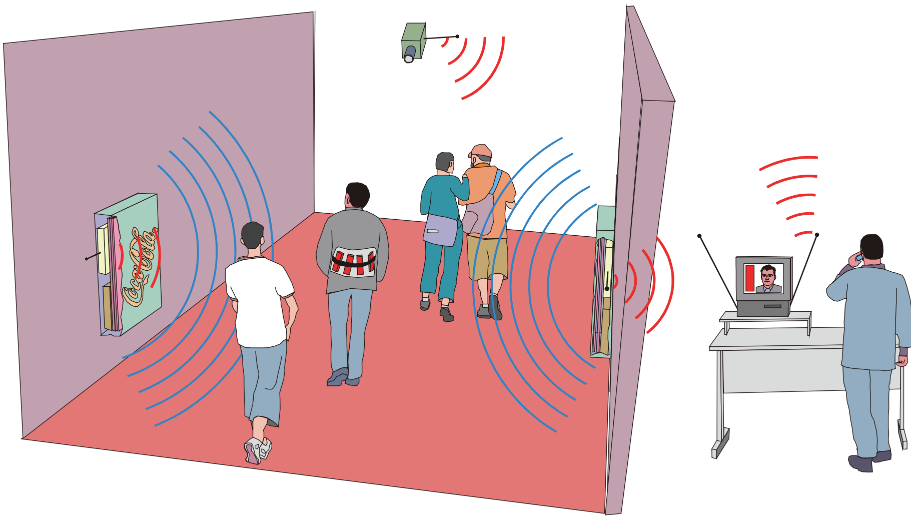

Figure 8. Schematic view of the full-scale system for detection of explosives on human body.

Example of a possible installation of a full-scale system is shown at Figure 8. The system can be installed anywhere in subways, corridors, lounges, mobile platforms etc. It continuously performs computer-aided inspection of all people and objects passing or standing in the system's sensitivity zone, and provides their 3D images as well as distinguished between metals and dielectrics and determines dielectric properties of all dielectrics. The resulting image with resolution about 1 cm, together with dielectric properties of the threat object, would allow one to recognize the concealed explosive and estimate its mass.

5. Conclusions

Gigahertz-range microwaves may be the best tool for quickly building safe and inexpensive devices for standoff detection of threat objects (guns, knifes, plastic bombs, improvised explosives) attached to human body.

The system based on gigahertz-range microwaves can perform secret inspection of passing people from distances of several meters. It can be installed on walls, ceilings, under floor, inside elevators, and disguised as information or advertising board.

DEVELOPMENT OF METHODS AND EQUIPMENT FOR DETECTION OF EXPLOSIVES' VAPORS IN THE ATMOSPHERE WITH LASER

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1. Introduction

Nowadays a lot of attention is being paid on the development of methods and instrumentation for detection of traces of explosives in the atmosphere. This necessity is caused by numerous cruel and inhuman acts of terrorism, which are being carried out throughout the world. Often terrorists' attacks are carried out by suicide-bombers, who are usually indistinguishable from other people in the crowd. In this connection, methods of standoff detection of traces of explosives in the air are of particular interest, since they can provide the possibility of non-contact (secret) detection of explosives or a suicide bomber.

Among many known methods of detection and identification of chemical compounds, only optical chemical analysis methods can provide standoff detection, because they use light waves (either absorbed or emitted by the object) as carriers of information. In the past decades, all optical methods practically without exception have undergone their second birth due to a great progress in the laser and optoelectronic technologies. Thus, recent advances in semiconductor lasers, optical fibers, and high-sensitivity matrix detectors based on CMOS technology made it possible to make Raman analyzers standard devices for routine measurements in chemical analysis [1]. Lidar methods also gain a wide use in monitoring the environment and in ecological control [2].

However, optical methods have so far found only limited application in detection of explosives, and many problems in the development of these methods are still to be addressed [3]. The difficulties in detecting the

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H. Schubert and A. Kuznetsov (eds.), Detection and Disposal of Improvised Explosives, 51–68.

explosives are caused, first of all, by extremely low concentration of the explosives' vapors in the atmosphere, since these substances are often low volatile. In this presentation we would like to attract attention to the following key aspects concerning application of remote laser sensing methods to the detection of explosives:

1. What is the potential of optical detection methods?
2. What are the conditions for their application to the detection of explosives?
3. Physical principles, which constitute the basis for optical detection methods, and comparison of efficiency of major optical effects of interaction between light and matter.
4. Overview of the advances in detection of explosives using optical methods.
5. Assessment of possibilities to create a remote optical sensor of explosives.
6. Research problems that must be solved in the course of development of laser detection systems.

2. Potential of Optical Detection Methods

How can optical methods be used to detect chemical compounds in the atmosphere? In order to estimate the feasibility of optical methods and to encourage instrumentation designers, we will first assess the minimum detectable concentration under favorable conditions (no external noise and other interfering factors). Let's consider how optical signals appear in the remote detection methods. Figure 1 depicts the optical arrangement, which illustrates the lidar detection and measurement principle.

The pulse of laser radiation interacts with the vapor of an explosive existing around the explosive device. The interaction yields an optical response, which is collected by an optical receiver. After spectral isolation and photo detection the detection signal is formed.

The main factors determining the signal power are the following:

- mean power of the laser radiation;
- efficiency of the radiation interaction with the matter;
- solid angle within which the scattered radiation is being collected;
- efficiency of the receiving optics and electronics.

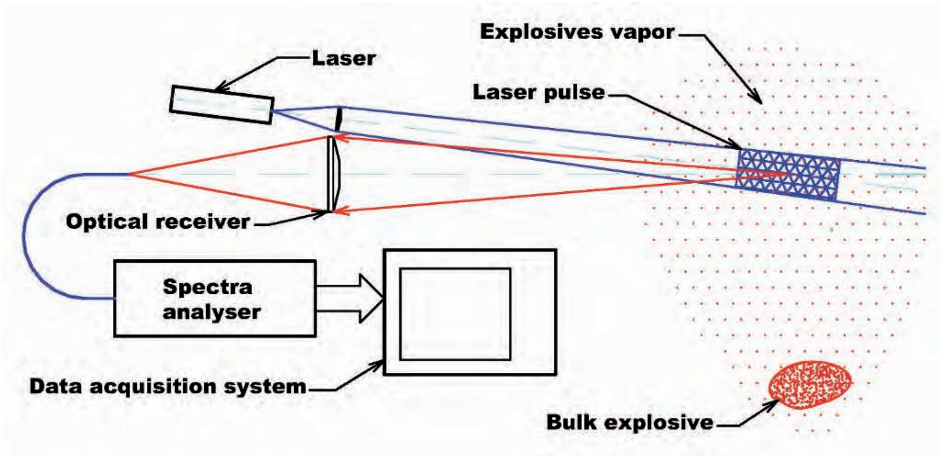

Figure 1. Block-diagram illustrating the operation principle of a lidar detector.

Taking into account the factors listed above, the mean number of photo counts per second recorded with such a generalized lidar detector can be estimated, within an order of magnitude, by the following expression.

$$n_x = \frac{P_l}{h\nu} \cdot \sigma_x \cdot c_x \cdot \Delta r \cdot Q \cdot \frac{S_o}{r^2} \cdot \tau \cdot \eta \tag{1}$$

where P_i is the mean power of laser radiation, $h\nu$ is the photon energy, σ_x is the absorption cross-section, c_x is the concentration of the vapor molecules, Δr is the spatial resolution, Q is the quantum yield of the reemission process, S_o/r^2 is the solid angle, within which the scattered radiation is being collected, S_o is the area of the receiving aperture, r is the sounding range, τ is the transmission of the receiving optics, η is the quantum efficiency of the photo detector. The process of laser radiation transformation into a response signal from the medium is schematically shown in Diagram 1. According to this diagram the mechanism of transformation can approximately be quantified as follows.

$$\overset{10^{18}}{n_l} \xrightarrow[\text{absorption}]{\sigma_x \cdot c_x \cdot \Delta r = 10^{-12}} \overset{10^{6}}{n_{abs}} \xrightarrow[\text{emission}]{Q=10^{-1}} \overset{10^{5}}{n_{em}} \xrightarrow[\text{propagation}]{\frac{S_o}{r^2}=10^{-3}} \overset{10^{2}}{n_{sig}} \xrightarrow[\text{conversion}]{\tau \cdot \eta = 10^{-1}} \overset{10}{n_x}$$

Diagram 1. Scheme of the laser radiation transformation into a response signal.

It is convenient to measure the signal in the number of the recorded photo counts. Thus a laser delivering radiation of 1-W mean power emits about 10^{18} photons per second (n_i in Diagram 1). Note, that the typical value of the absorption cross-section of most vapors in the near UV and visible ranges is $\sigma_x = 10^{-20}$cm^2.

Let us take the concentration of the vapor to be at the level of $c_x = 10^7$cm^{-3}, or 1 ppt in relative units under standard atmospheric conditions. We assume spatial resolution to be 10 cm. The assumed values of other parameters are shown in Diagram 1.

As it follows from the diagram, 10^7 molecules of the substance per cubic centimeter will generate an optical response to the incident radiation of 1-W mean power sufficient to produce signal pulses at the output of the detection system at the level 10 Hertz, provided that factors due to quantum efficiencies of the interaction and photo detection processes and transmission of the optical system amount to 10%. One can show [4] that in the absence of noise it is sufficient to have 6 photo counts at the output of the detection system to reliably detect a signal with Poisson statistics. This means that in this idealized case one has a 1.5 times reserve in system sensitivity. Generally saying, the above considerations show, that theoretically the inherently non-contact and standoff optical methods have quite high sensitivity and thus can be successfully applied to the detection of extremely low amounts of chemical substances.

There are many experimental studies, many of which became classical, devoted to detection and measurements of gases and vapors by use of optical methods [5]. For example in [6] measurements of OH radical concentration of 5×10^6 cm^{-3} are reported. In [7] a laser-induced fluorescence technique has been developed, which made possible measurements of the CN radical content at the level of 10^8 cm^{-3}. In the case of metal vapors characterized by much higher cross-sections of interaction with light, the achieved threshold sensitivities of the detection using resonance fluorescence are even lower. Thus, for lead vapor the threshold concentration sensitivity was demonstrated to be at the level of 250 cm^{-3}, while for sodium vapor in the mesosphere it was at the level of several atoms per cubic centimeter [8,9].

Thus, the sensitivity of optical methods estimated theoretically and demonstrated in practice is sufficiently high.

3. Conditions for Applying Optical Methods to the Detection of Vapors of Explosives in the Atmosphere

Detecting the presence of explosives in the volume by instrumental means is, as a rule, a part of security measures, and therefore it should meet the requirements to security systems. Among these requirements are: efficiency, reliability, standoff detection, secrecy, and safety. However, in addition to these conditions it is very important to identify the object to be detected and to address the questions of what is the mean concentration of the explosive in the vapor phase within the volume under control, and what is the configuration of the vapor cloud and how the concentration of the vapor is distributed across the cloud. It is also useful to understand the range of concentrations, to which the instrument has to be sensitive.

In Table 1 the requirements to the system intended for detection the explosives are summarized.

Table 1. General requirements to the system intended for detection the explosives.

Type of substance	Explosives
Phase state	Vapor
Concentration, ppt	0.1-10000
Detection rate, s	1-10
Range, m	1-10
Special requirement	Secrecy

Table 2. The list of most widely used explosives.

N	Compound	N	Compound
1	2,4,6,-trinitrotoluene(TNT)	11	Nitrocellulose (NC)
2	Pentaerytritoltetranitrate (PETN)	12	1,3,3-trinitroazetidine (TNAZ)
3	Hexahydro-1,3,5,-triazine (RDX)	13	Nitroglycerin (NG)
4	Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazine (HMX)	14	Picric acid (PA)
5	Triacetone triperoxide (TATP)	15	Ammonium nitrate (AN)
6	Hexamethylenetriperoxidediamine (HMTD)	16	Ammonium perchlorate (AP)
7	Methyl-2,4,6-trinitrophenylnitramine (Tetryl)	17	Ammonium dinitramide (ADN)
8	Ethylene glycol dinitrate (EGDN)	18	Potassium nitrate
9	Triaminetrinitrobenzene (TATB)	19	Potassium perchlorate
10	3-nitro-1,2,4-triazol-5-one (NTO)	20	CI-20

Table 2 lists the most widely used explosives [10]. Of course this is not a complete list of substances, with which remote detection will deal in practice. From the standpoint of optical methods it is most important to have information on the molecular structure and on the types of chemical bonds, since they determine spectroscopic properties of chemical compounds.

Data collected in Table 3 give the information on the vapor density of some explosives in the atmosphere under conditions of non-restricted vaporization [11]. These data can be used as the basis in developing the systems for detection of explosives.

Table 3. Data on volatility of some explosives.

Compound	Vapor density (order of magnitude)		
	The number of molecules of the explosive per 10^{12} molecules of air, (ppt)	The number of explosive's molecules per 1cm^3 of air	The mass of the explosive per 1cm^3 of air, g
NG	10^6	10^{13}	10^{-9}
TNT	10^4	10^{11}	10^{-11}
PETN	10^0-10^1	10^8-10^9	10^{-14}-10^{-13}
RDX	10^0	10^8	10^{-14}
C-4 (91%RDX + 9% of a sticker.)	10^{-1}	10^7	10^{-15}
EGDN	10^8	10^{15}	10^{-7}

The above tables formulate the conditions for applying laser-based explosives' detectors; the types of these chemical compounds, and the level of vapor concentrations to be expected near the explosives device. One can note, that the concentration of explosives depends on the temperature and packing [12]. For this reason the above estimations should be treated as approximate.

4. Physical Principles, which Constitute the Basis for Optical Detection Methods

All optical methods for determining chemical composition of air rely on the basic phenomena of interaction between light and matter. The basic fact is that energy exchange occurs between the incident electromagnetic field and molecules of the substance during interaction. In this case the reemitted wave will bear information on the structure of energy levels in molecules. It

is the uniqueness of the energy level structure of molecular species that forms the fundamental principle of recognition of chemical compounds.

To better understand the phenomenological basis of the optical detection methods it might be useful to consider the whole set of effects of interaction between matter and radiation from the standpoint of their practical use. Figure 2 shows a diagram of such effects, which allows one to analyze the feasibility of their use for detection of explosives.

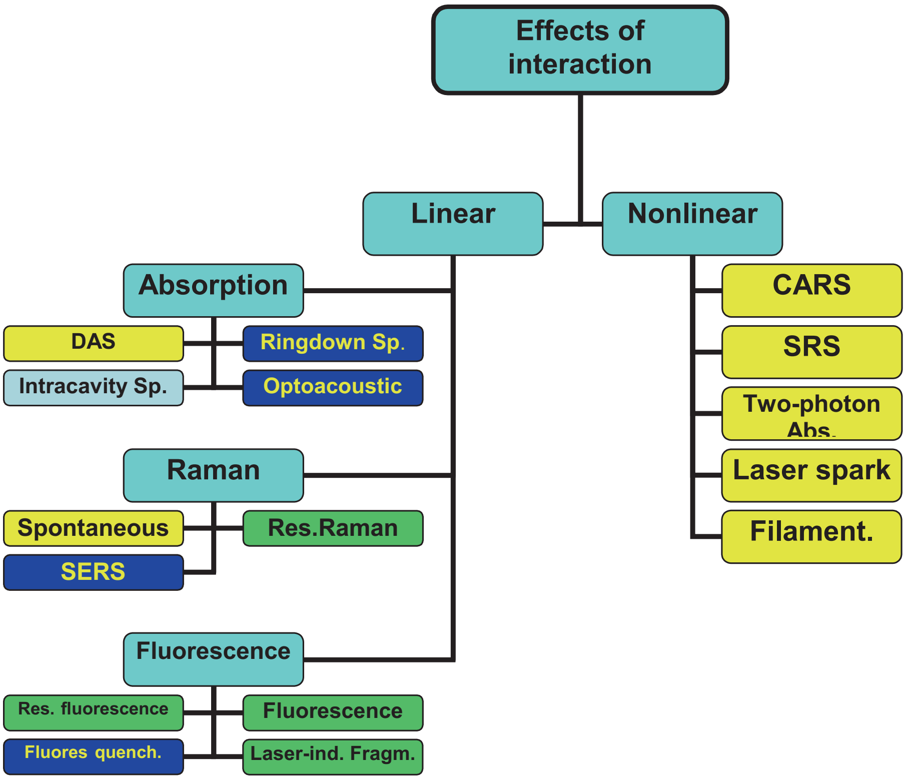

Figure 2. Diagram of the effects of interaction between the matter and radiation.

On Figure 2 the effects are divided into two groups: linear and nonlinear. Linear effects have been known for a long time, while study of nonlinear effects have only become possible with the advent of lasers, the light sources capable of emitting coherent radiation of high power density.

Linear interaction effects have found many applications in chemical analysis as the basis for various analytical technologies. Linear effects are split into three main groups by the interaction type: light absorption, spontaneous Raman scattering of light, and fluorescence. These effects are used in the majority of analytical techniques developed so far.

Absorption is the effect of interaction between radiation and mater, which results in that a portion of radiation energy is absorbed by an atom or a molecule, and this portion then can be transformed into other forms of energy, for example, into heat. Each molecular species has a unique absorption spectrum. The absorption spectrum can be obtained in the form of a transmission spectrum, the reflectance spectrum, the spectrum of attenuation of the return signal (in lidar technique), as well as in the form of spectrum of optical losses of a resonator, and so on. Analysis of absorption spectra allows one to identify the species absorbing the light. Absorption spectra of various substances recorded in the infrared wavelength region are normally most informative, since they are formed mostly due to unique combinations of the vibrational and rotational molecular motions. Although the technology of IR-spectroscopy is being permanently improved, there are still many issues to be addressed in order to fully take advantage of the potential information provided by the IR region. Table 4 presents information about typical threshold sensitivities of different methods, which use the effect of light absorption. It can be seen from Table 4, that all these methods have high sensitivity, but only one of them (DAS technique) is a standoff method.

Table 4. Detection thresholds of different light absorption methods.

Method	Detection threshold	Sampling needed, yes/no
DAS	ppb	no (long paths)
In-resonator	ppb	yes
Ringdown	ppb	yes
Optoacoustic	ppb	yes

However, this technique produces good results only for the case of long-path absorption, and hence it has found practical application only in ecological monitoring of the environment.

The effect of spontaneous Raman scattering of light can briefly be characterized as interaction process of inelastic scattering of photons on molecules of a substance. This process results in the change of the energy state of interacting molecules and creation of photons with energies different from those of incident ones [13]. Raman spectra consist of bands shifted with respect to the frequency line of the exciting radiation. The spectral shifts of the bands are determined by the energy of vibrational-rotational motions of molecules. As in the case of absorption spectra, Raman spectra also have high information content. However, in contrast to the absorption spectra, the positions of Raman spectra on the wavelength

scale are determined by the wavelength of the exciting radiation, which can be optimized when necessary.

In Table 5 detection thresholds for Raman methods are presented [14]. One can see, that sensitivity of Raman methods is insufficient for detecting traces of explosives in the atmosphere.

At the same time, if the frequency of the exciting radiation approaches the allowed transition of the molecule, the efficiency of Raman scattering undergoes resonant increase of about four orders of magnitude and even higher [15]. Therefore, resonance Raman technology can be a good candidate for use in detection of explosives, being an inherently standoff technique.

Table 5. Detection limits for Raman scattering methods.

Method	Threshold sensitivity	Sampling need, yes/no
Spontaneous Raman	ppm	no
Resonance Raman	ppb	no
Surface enhanced Raman scattering SERS	ppt	yes

Fluorescence is a classical phenomenon of optical interaction, which is being widely used in practice. The fluorescence effect consists in the molecule or an atom excited due to absorption of incident radiation emitting photons while relaxing from an excited to the ground state [16]. Actually, it does not mater how the molecules or atoms are excited, but in the case of excitation by laser radiation it becomes possible to conduct remote spectral analysis. Typically, fluorescence has high quantum yield. This is explained by the fact that interaction between incident radiation and the matter occurs resonantly. It is for this reason that the fluorescence methods have high sensitivity, while at the same time being standoff techniques.

Table 6 gives the data on the threshold detectability of the fluorescence methods[5]. It is obvious that such sensitivity well fits the requirements to the methods of detecting the explosives. For this reason the fluorescence deserves special attention as a candidate in developing highly sensitive detectors of the explosives and their traces in the atmosphere.

Table 6. Detection thresholds of fluorescence methods.

Method	Detection limit	Sampling need, yes/no
Molecular fluorescence	ppt	no
Resonance fluorescence	10^2 cm^{-3}	no
Fluorescence quenching	ppt	yes

Thus we have briefly overviewed the possibilities of using linear effects of interaction between matter and light in constructing methods for standoff detection of explosives in the atmosphere. It seems, that in principle fluorescence and resonance Raman scattering possess the highest sensitivity among optical methods that can be developed for standoff detection of explosives.

A detailed analysis of nonlinear effects of optical interactions is outside the scope of this publication. However, it is worth mentioning that significant advances in the available equipment, particularly in femtosecond lasers, opens new perspectives for using nonlinear effects in standoff gas analysis.

In the above discussion optical interaction effects were analyzed as such, without paying attention to the details of their occurrence in the atmosphere. At the same time the ambient air may lead to additional factors that can affect and modify scenarios of optical interactions. Among these are elastic scattering of light by atmospheric aerosols and molecules, quenching of the fluorescence, broadening of spectral lines, and so on. Thus, the elastic scattering of light in the atmosphere yields an optical interference, which masks the signal at the shifted frequency. Suppression of such interference requires a spectral device. The required suppression level can be estimated from the ratio of the corresponding cross-sections of the relevant interaction processes. Table 7 gives the data on the efficiency of some interaction processes in the atmosphere [17]. These data allow one to estimate the influence of stronger effects when they are simultaneously excited in the atmosphere on sensitivity of detection systems.

Table 7. Comparison of the efficiencies of optical interaction processes in the atmosphere.

Optical effect.	Frequency	Cross-section of the interaction, cm^2	Detected component
Mie scattering	$\nu r = \nu o$	10^{-26}-10^{-8} (aerosols)	Aerosol Particles
Raleigh scattering	$\nu r = \nu o$	10^{-26}-10^{-23}(Res.)	Atoms Molecules
Spontaneous Raman scattering	$\nu r \neq \nu o$	10^{-29}-10^{-26}(Res.)	Molecules (Atoms)
Fluorescence	$\nu r = \nu o$ $\nu r \neq \nu o$	10^{-26}(Quenched) 10^{-24}(Quenched)	Atoms Molecules
Absorption	$\nu r = \nu o$	10^{-20}	Atoms Molecules

5. Advances in Detection of Explosives Using Optical Methods

Although optical spectroscopy is widely used in measurements of low concentrations (at the background level) of the trace atmospheric gases, they have not yet found wide application in explosives detection. This is explained, in part, by tough conditions of detection (low concentration, small volumes, interference) and in part by specific spectroscopic features of the explosives themselves. However, recently these methods have been attracting increasing interest in view of their use as the conceptual basis for future detection systems.

In the development of any spectroscopic detection system the key information needed is the information on the frequencies and intensities of the absorption and/or emission spectra of the substances to be detected. Gradually such data are being compiled in literature, though not in the form of accessible databases, like HITRAN for atmospheric gases [18].

5.1. IR SPECTROSCOPY

Data on the spectroscopic properties of explosives in the infrared region are most complete, however, they can hardly be useful for developing a standoff explosive detector. Nevertheless, there are some studies published in the literature on attempts to apply IR-spectroscopy methods to detection and identification of the explosives traces on the surface of the explosive devices or in soil after condensing samples [19,20]. Among practical applications of IR techniques is the method of diffuse-reflectance IR-Fourier (DRIFT) spectroscopy of surfaces [21].

Due to extremely low concentrations, use of the IR techniques in detection of explosives' vapors is limited to indirect recording of the absorbed energy such as optoacoustic detection or laser interferometric calorimetry. Another promising technology is the so-called cavity ringdown spectroscopy (CRDS).

5.2. RAMAN SPECTROSCOPY

The Raman effect has found its application to explosives detection only recently, while Raman spectra of many explosives have been well studied much earlier. This is largely the result of significant advances in semiconductor lasers, and matrix photo detectors based on CCD/CMOS technologies. At present, spontaneous Raman scattering has been successfully applied to *in situ* detection and identification of explosives, as well as in criminology to the analysis of fingerprints on presence of traces

of explosives. Table 8 gives some information on application of Raman spectroscopy to explosives detection [18].

The SERS effect, discovered by Fleischmann et al. in 1974 though difficult to use in remote detection, is worth mentioning as it really competes in sensitivity with dog's nose and allows one to detect mines in real minefields [22]. The idea of SERS effect is based on enhancement of Raman scattering intensity from molecules, which are adsorbed on a rough metallic (copper, gold) surface. It is likely that the mechanism of this enhancement is related to locally high-strength electromagnetic fields that can appear at the surface inhomogeneities. In this technique the air sample is blown over the rough surface of the SERS cell, which is illuminated with radiation of a semiconductor laser. The frequency-shifted peaks in the spectra are recorded and then assigned to relevant substances. Figure 3 illustrates the SERS principle in application to detection of mines on a minefield [23].

Table 8. Use of Raman spectroscopy in explosives detection.

Technique	Species	Information or data
Raman	RDX	632.8 nm excitation
Raman	NG, PETN, RDX, TNT	20–40 ng detected on activated charcoal
FT-Raman Semtex	RDX, PETN	Component identification
FT-Raman	2 materials	10 μm sample size
FT-Raman	RDX	Vibrational frequencies used to estimate impact sensitivity
Raman microscopy	RDX, PETN	1 μm^3 sample size
Raman	PETN	Fiber-optic probe
FT-Raman	HMX, RDX, PETN, nitroguanidine, nitrocellulose	
FT-Raman	HMX, RDX, PETN, nitroguanidine, nitrocellulose	Low-frequency modes
SERS	TNT	1 pg TNT detected
Raman microprobe	RDX	
Raman imaging	RDX, PETN	
Single-pulse Raman	TNB, MATB, TNB, MATB	

As for the resonance Raman effect, only few papers devoted to this particular application can be found in literature. However, this effect seems to be a promising technology in connection with recent advances in laser

excitation sources in the UV, and new possibilities due to two-photon excitation.

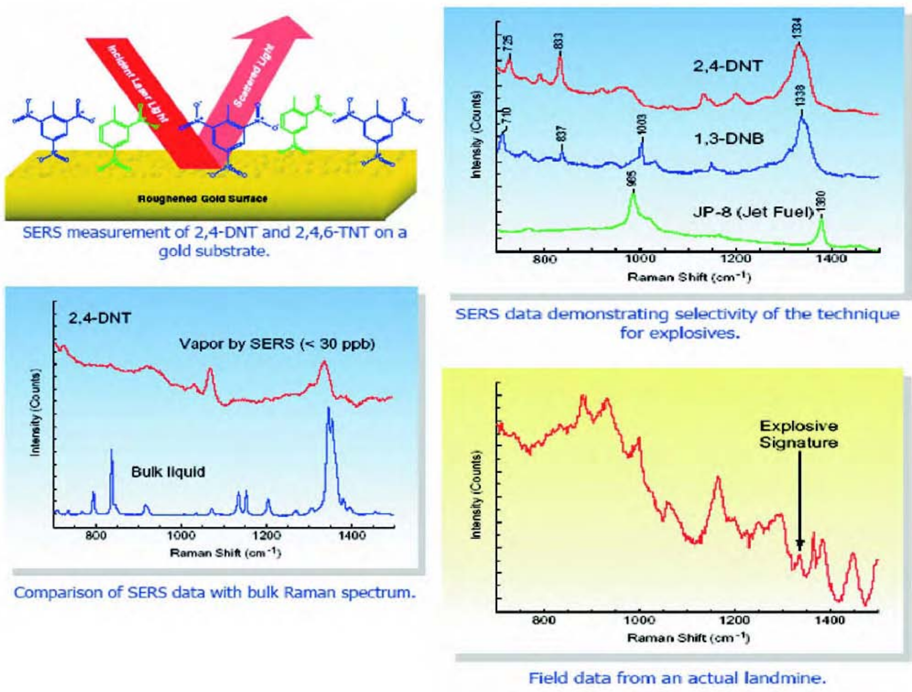

Figure 3. Application of SERS to detection of explosives.

5.3. SPECTROSCOPY IN THE VISIBLE AND UV SPECTRAL REGIONS

All nitroaromatic and nitroaliphatic compounds have wide absorption bands in the spectral range at wavelengths shorter than 300 nm. Unfortunately, many organic compounds have similar absorption bands in this spectral region. This circumstance essentially limits direct identification of explosives absorbing light in this region. However, the information on the spectral features of the electron energy states of explosives is very important for proper use of other more sensitive techniques, like resonance Raman and fluorescence. Table 9 gives some information on the use of spectroscopy of the visible and UV regions in explosives detection [18].

Thus, in [24] it was experimentally found that it is optimal to excite resonance Raman scattering of TNT by radiation with wavelengths from 200 nm to 300 nm, while for RDX and PETN the optimal wavelengths are at about 200 nm. In [25] one can find information on the fluorescence properties of the ANFO (ammonium nitrate/fuel oil mixture) compound.

Table 9. Use of spectroscopy of the visible and UV regions in explosives detection.

Technique	Species	Information or data
Spectrophotometry	TNT, RDX, PETN	Absorption spectra 200–400 nm
Photoacoustic spectroscopy	RDX, HMX, PETN, TNT, 14 other	400–1600 nm
Chemiluminescence	RDX, PETN	During thermal decomposition
Optical	Nitrocellulose deflagration	Detect burning rate
Fragment	TNT fluorescence	Detect NO fragment at 226 nm
IRMPD C fragment	RDX, HMX fluorescence	Detect OH fragment

5.4. FRAGMENTATION OF EXPLOSIVES AND FRAGMENTS DETECTION

The idea of this approach is to split the molecules of the target compound into fragments that may be easier to detect. Most often, the molecules are fragmented thermally or optically. Laser fragmentation allows one to break the molecules remotely. The fragmentation may also be followed by fluorescence of fragments. Thus in [26,27,28] the vapors of TNT were detected by observing the fluorescence of NO, excited by the same radiation at 226 nm wavelength. In the study of explosives fragmentation [29] such simple compounds as HCN, CO, H_2CO, NO, N_2O, NO_2, HNCO, HONO, NH_2CHO and HCOOH have been observed. In this connection, it is clear that spectroscopic properties of these fragments are very important for the development of the explosives detection methods.

$$R\text{-}NO_2\,(s) \xrightarrow{h\nu\,(uv)} R + NO\,(X^2\Pi) + O$$

Diagram 2. Laser fragmentation of TNT.

Thus, one can conclude, that the use of emission optical effects, such as resonance Raman scattering and fluorescence, could be the most promising way of achieving the highest possible sensitivity of a remote laser detector of explosives. The use of laser fragmentation would allow one to reduce the task of explosives detection to the detection and identification of simpler molecules, whose spectroscopic properties are known quite well.

6. Assessment of Possibilities to Create a Remote Optical Sensor of Explosives

Table 10 summarizes data on the optimal wavelength of radiation for exciting fluorescence of some fragments of explosives. One can see, that the excitation wavelengths are in the near UV. This means that the exciting radiation is invisible, while being accessible with tunable laser sources.

Table 10. Radiation wavelengths for excitation of some explosives fragments.

Molecule (atom, radical)	Transition	Laser wavelength, nm	Emission wavelength, nm
NO	$A^2\Sigma^- - X^2\Pi$	226	248
OH	$A^2\,\Sigma^+ - X^2\Pi$	281	312
NH	$A^3\Pi - X^3\Sigma^-$	336	336
CH	$B^2\Sigma^- - X^2\Pi$	387	390
CN	$B^2\Sigma - X^2\Sigma$	388	421
NO_2	$A^2B_1 - X^2A_1$	400	440
CH	$A^2\Delta - X^2\Pi$	413	430

Table 11 gives data on the absorption cross-sections of some fragments and on the quenching factors for them [17]. These data were used in calculating the efficiency of fluorescence under atmospheric conditions for such fragments as NO, OH, and NO_2. One can note, that the NO radical has the highest efficiency in fluorescence and thus it is the most promising candidate for an indicator of the presence of explosives.

Table 11. Cross-sections of absorption, fluorescence and the quenching factor of some explosives fragments.

Molecule (radical)	Radiative lifetime, s	Lifetime of excited state at P=1atm, s	Quenching factor	Absorption cross section, cm^2	Fluorescence. cross section, cm^2/sr
NO	-	-	$3x10^{-3}$	$1.3x10^{-18}$	$3x10^{-22}$
OH	$8x10^{-7}$	10^{-9}	$10^{-2}-10^{-3}$	$1.2x10^{-17}$	10^{-20}
NH	-	-	-	-	-
CH	-	-	-	-	-
CN	-	-	-	-	-
NO_2	$4.4x10^{-5}$	$1.4x10^{-10}$	$2.5x10^{-5}$	$2.8x10^{-19}$	$5.6x10^{-25}$
CH	-	-	-	-	-

Let us estimate sensitivity of a laser detector of explosives based on the fragmentation of the target compounds and fluorescence identification of the NO radical. Tentative calculations give the performance parameters of such a microlidar detector presented in Table 12.

Table 12. Possible performance parameters of a laser detector of explosives.

Parameter	Value
Mean power of the laser emission, W	1
Wavelength of the exciting radiation, nm	226
Receiving area, m^2	0.1
Throughput of the optoelectronics channel, %	10
Central frequency of the fluorescence band, nm	248
Spatial resolution, m	0.1

Turning back to formula (1) and making use of the above technique of assessment, one can calculate, using data from Tables 11 and 12, the time necessary for detection of the NO radical in atmosphere at density of $10^7\ cm^{-3}$ at the distance of 10 m and range resolution of 10 cm. The calculated time turns to be of the order of 1.2 s.

7. Conclusions

The above estimations might turn to be too optimistic and will be corrected in practice, but the goal of this publication was to try to find the way of research that would enable us to achieve the task of creating a standoff detector of explosives vapors in the atmosphere. From the standpoint of experience of species detection gained in laser sensing of the atmosphere, the search for solution of this problem can be carried out on the basis of emission effects, accompanying interaction of laser radiation and trace substances, such as resonance Raman and fluorescence. Recent advances in lasers and optoelectronics raises hopes for solving the task of standoff laser sensing at new level of technology. However, technical realization of new potentialities of laser-based standoff detectors is in urgent need for the initial data, which are yet lacking. In our understanding, the following problems are to be addressed in order to achieve the task.

- Study of the spectroscopic properties of explosives in the UV, including the vacuum UV region.
- Investigation into the laser fragmentation of the target compounds.
- Study of the spectroscopic properties of fragments in the UV region.

- Search for new efficient schemes of fluorescence excitation in explosives.
- Study of new ways to enhance the efficiency of the emission processes by use of nonlinear and non-stationary conditions of excitation.
- Study of the masking effect of minor gaseous constituents of the atmosphere on the operation of the explosives detection with laser.

Achieving these tasks, combined with the experience already gained in the spectroscopy of extremely weak optical signals, would make a reality construction of a laser detector of explosives traces in the atmosphere.

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DETECTION OF IMPROVISED EXPLOSIVES DEVICES (IED) BY USING TAGGED NEUTRON BEAMS

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Abstract. Non-destructive inspections of explosive devices making use of a 14 MeV tagged neutron beam and scintillation detectors (Tagged Neutron Inspection System, TNIS) have been simulated in laboratory conditions. The tagged neutron beam is produced by detecting the associated alpha particle emitted in the D+T reaction by means of YAP:Ce scintillators. The system has proven capable of identifying hidden explosive objects. The prototype of a portable neutron generator with embedded YAP:Ce detectors was developed successfully. Consequently the tagged neutron system has been proposed for inspections of cargo containers in projects funded by NATO and the European Union. In this respect second generation devices are under development. Results will be presented in this report about further applications of the TNIS in a real time scanning of vehicles carrying a large quantity of explosive as in terrorist attacks.

Keywords: 14 MeV tagged neutron beams, non destructive analysis, explosive detection.

1. Introduction

The threat of terrorist use of explosive devices and chemical, biological or radioactive agents has become realistic since Bombing of Pan Am Flight 103 at Lockerbie, Scotland on 21 December 1988 and the SARIN attack in the Tokyo subway system on March 20, 1995. A long series of events started more recently with the tragic events of September 11, 2001, the latest being the recent bombing in London. The possibility of further

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H. Schubert and A. Kuznetsov (eds.), Detection and Disposal of Improvised Explosives, 69–85.

terrorist actions against civil populations is one of the most important issues on the international political agenda [1].

The contrast of the terrorist actions involves several different tasks. Among the others, the illicit trafficking of explosives through conventional commercial networks (air, maritime and terrestrial) represents therefore a real challenge to civil security for future years [2].

Manual and visual inspection of large commercial payloads at terrestrial borders (trucks), seaports (containers) and airports (check-in luggage) would not be a viable solution both from efficiency considerations and for legal reasons. It is mandatory to realize standoff integrated inspection systems by means of imaging and analytical methods based on a sound technology to identify threat materials [3]. In this respect, the key to distinguishing explosives from benign materials is the use of the elemental analysis. While the X-ray or gamma-ray based systems can give good precision density measurements with high resolution three-dimensional images, these systems provide at best only gross information about the elemental content of the inspected item (low Z vs. high Z discrimination). Neutron interrogation, on the contrary, offers the possibility of measuring the elemental density of most elements in materials independent from their particular structure [4,5].

The use of neutron induced reactions for nondestructive bulk elemental analysis is well documented [6,7]. All neutrons, in particular fast neutrons, are well suited to explore large volume samples because of their high penetration in bulk material. The detection of hidden explosives [8] is achieved by determining the elemental ratio of C, N, O nuclei from the intensity of the characteristic gamma-rays produced in fast neutron induced reactions. This technique is known as Fast Neutron Analysis (FNA) [9].

One important limitation of the fast neutron inspection techniques is the fact that the neutron source and the gamma-ray detectors are placed as close as possible to the inspected object to increase the detected signal. In this situation, the signal-to-noise ratio depends on the fraction of neutrons that reach the sample and on the solid angle subtended by the gamma-ray detector. The spectra are thus dominated by the gamma-rays originated close to the neutron source and to the gamma-ray detector. Consequently, it is difficult to search for hidden threat inside large volume of cargo material, above and beyond the basic problems related to the neutron and gamma-ray attenuation inside the cargo.

In the last 3 decades, significant efforts have been made to produce tagged neutron beams with compact sealed neutron generators. This is achieved routinely in open-ended accelerators by using the well known Associated Particle Technique, when the $T(D,n)^4He$ or the $D(D,n)^3He$

neutron source reactions are used [10]. Examples of systems using the associated particle technique with sealed neutron generators are reported in Refs. [11,12].

Within the EXPLODET (EXPLosive DETection) project [13,14], a tagging system for the production of tagged neutron beams has been extensively studied at the Neutron Generator Laboratory at Ruder Boskovic Institute in Zagreb (Croatia) [15].

The results obtained with such system can be summarized in the following points:

1. The use of tagged neutron beams improves the signal to noise ratio by electronically selecting the gamma-rays from the voxel defined by the tagging detector and by the neutron time of flight.
2. The size of the inspected voxel strongly depends on the segmentation of the tagging detector and on the overall time resolution of the alpha–gamma coincidences. Fast gamma ray detector and fast and highly segmented alpha particle detection systems are needed if small objects have to be interrogated.
3. The use of fan beams allows the simultaneous measurement of gamma-rays emitted in the neighboring voxels thus allowing the online subtraction of the background from the suspect item.

Recent studies on the above technique point to the development of a portable sealed neutron generator with the neutron tagging detector embedded into the system. Such development has been successfully performed in a collaborative project between the Physics Department of the Padova University, INFN and EADS-SODERN [16]. In more recent work, a number of different alpha particle detector configurations, designed for the production of tagged neutrons, has been tested in our inspection system which is in operation at the Neutron Generator Laboratory of the Ruder Boskovic Institute (IRB) in Zagreb, Croatia.

Another aspect of the problem is the detection of hidden explosive in vehicles that are used in suicide bomber attacks worldwide. A specific requirement in this case is the fast scan of vehicles operated at sufficiently large distance from the target itself, to avoid damage in case of explosion. Neutrons are also in this case an interesting probing radiation, thanks to their penetration capabilities. On the other hand, the technique of looking to the gamma rays to perform elemental analysis is to slow to be applied in such context. Less specific but rapid signature of the presence of large quantity of hydrogenated materials can be obtained by looking at the transmission and scattering of fast neutrons. Results obtained from Monte Carlo simulations will be also presented in this paper.

2. The YAP:Ce Scintillator Tagging System

A YAP:Ce scintillator [17] of 4 cm diameter and 0.5 mm thickness was selected to be inserted into a sealed neutron generator. The YAP:Ce exhibits, indeed, several characteristics that are very well suited for this task: excellent mechanical and chemical properties, radiation hardness, fast response and high light output [18]. The scintillator was mounted on the CF63 flange equipped with a sapphire window (3 mm thick, 48 mm diameter) without any optical grease, as required in the sealed neutron generator manufacturing procedure [19]. The surface of the YAP:Ce crystal was coated with a layer of 1 mg/cm^2 of metallic silver to maximize the light collection, stop the elastically scattered deuterons and protect the crystal from the UV glow inside the neutron generator. Since the counting rate capability and the time resolution are the major goals of the present application, we used a small diameter fast PMT Hamamatsu R1450, without light guide. The tagging system (i.e. the YAP:Ce mounted on the optical flange plus the PMT and the associated front-end electronics) has been tested with neutrons produced in the D+T reaction making use of the 150 kV neutron generator at the IRB. Details are given in Ref. [15].

For the tests reported in Ref. [15], a 5.5 mm diameter collimator was positioned in front of the YAP:Ce detector in order to limit the size of the tagged neutron beam at the inspection plane which is defined by a BaF_2 detector array.

The time distribution of the YAP:Ce–BaF_2 coincidences was measured irradiating a 10×10×10 cm^3 graphite sample placed in the center of the measured tagged neutron beam. The measured overall time resolution is δt=1.6 ns [FWHM]. This value has to be corrected for the jitter in the time of flight of the alpha particles and for the spread due to the different neutron flight paths inside the volume of the graphite block. This contribution, estimated by Monte Carlo simulations, is δt = 1.3 ns [FWHM]. The intrinsic time resolution of the system is then δt = 0.9 ns [FWHM], which corresponds to a position resolution of about 5 cm along the neutron flight path [15].

3. Detection of Real Explosives

The sub-nanosecond time resolution of the system was exploited to inspect suitcases filled with different materials and containing “hidden” explosive devices, different voxels being defined by selecting windows in the time of flight spectrum. For these measurements a large Anti-Tank (AT) landmine was available at the Neutron Laboratory at IRB [15].

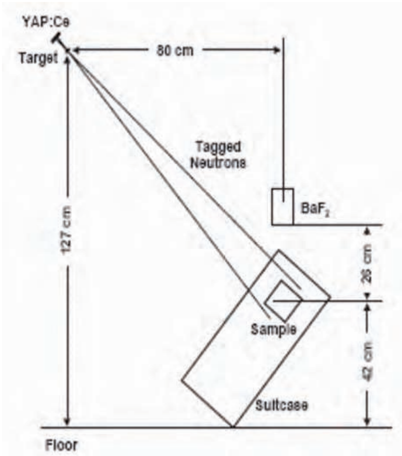

Figure 1. Layout of the system in operation at the Neutron Laboratory at IRB, in Zagreb (Croatia). The deuteron beam is exiting the figure.

In order to perform the tests, a standard hard plastic suitcase was positioned under an array of BaF_2 detectors, as shown in Figure 1. The suitcase was filled with different items including clothes and cardboards in order to simulate a realistic situation during airport inspections. The suitcase was positioned at the centre of the neutron beam, tilted by about 45 degrees so that the tagged neutron beam hits the sample normally to its surface. An AT landmine, type TMA-1A, was introduced into the suitcase. The TMA-1A is filled with 5.5 kg of TNT ($C_7H_3N_3O_6$). The explosive is contained in a plastic case with 31 cm diameter and 10 cm height. The TNT has the same diameter but it is only 7 cm high. The energy spectrum of the TMA-1A mine is shown in Figure 2. Due to the large content of TNT and the presence of the plastic case the peaks of carbon and oxygen are clearly seen in the spectrum. On the contrary, the signatures of the nitrogen at Eg=2.30 and 5.10 MeV are not clearly seen..

A further analysis has been performed to discriminate between the contribution of TNT and that due to the plastic case. Since the identification of explosive material is obtained by measuring elemental ratios (as C/O), it is important to discriminate the effects of the plastic case from the content, when possible. In this mine, indeed, the TNT bulk is separated from the upper side of the plastic case by a 3 cm air gap.

We have defined two time gates, the first one associated to the time of flight of the neutrons that hit the plastic case, and the second one to the time of flight of the neutrons that interact with the TNT inside the mine. The

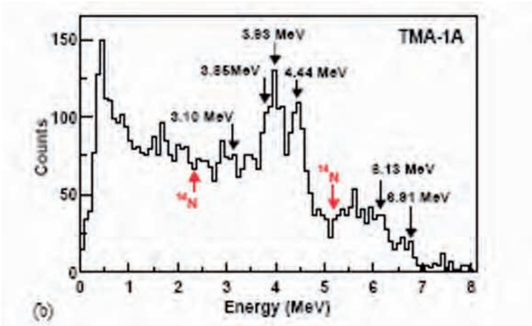

Figure 2. Energy spectrum of the TMA-1M mine.

measured gamma-ray spectra associated with the two time selections are reported in Figure 3.

From the two spectra in Figure 3, the yield ratio for two different energy regions (Y(Eγ=4.1–4.8 MeV) / Y(Eγ=5.1–7.1 MeV)) has been extracted. This value is 0.56+/-0.04 for our "TNT voxel" and 1.54+/-0.26 for the "plastic voxel". The yield value measured for the "TNT voxel" compares well with the value obtained in a separate calibration run in which a material with a C/O ratio close to that of the pure TNT has been irradiated. The comparison with the calibration run demonstrates that we were able to separate the voxel of the plastic case and of the TNT inside the TMA-1A landmine.

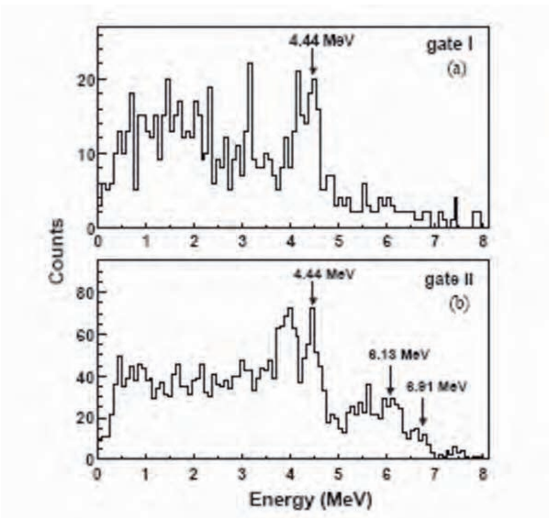

Figure 3. Energy spectra obtained selecting two different time of flight regions.

4. Studies on Alpha Detector Position Sensitivity

A portable Tagged Neutron Inspection System (TNIS) using the YAP:Ce detector has been developed recently in collaboration with SODERN (France). The portable TNIS has been tested by detecting the coincident gamma-rays produced in the irradiation of a graphite sample by means of a standard NaI(Tl) scintillator. The time resolution of the system has been measured to be about $\delta t = 5$ ns, which implies a resolution along the neutron path of about 25 cm. With this system the inspected volume element (voxel) is of about 35 cm diameter and 25 cm height at a distance of 50 cm from the neutron source [16].

A substantial reduction of the voxel dimensions is needed in handling higher count rate or when required by specific inspection tasks.

4.1. READ-OUT BY "CENTER OF GRAVITY"

In order to produce multiple neutron beams of variable sizes, a study of the position sensitive alpha-particle detector has been performed. Two systems have been built and tested with the 40 mm diameter YAP:Ce crystal: the first one uses 3 fast PMT's Hamamatsu R4141 (13.5 mm diameter) and the second one employs a 2×2 multianode PMT Hamamatsu R5900U-00-M4 (18×18 mm^2) [20].

In both cases, the PMT photocathode diameter is smaller than the YAP:Ce crystal. Consequently, the light collection efficiency depends on the relative position of the alpha-particles on the detector surface with respect to each PMT. Such effect can be used in order to link the measured pulse height values to the distance r between the alpha-particle and the PMT center. The pulse height distributions have been studied for different positions of an alpha-particle source (^{241}Am) placed behind a mask having several 1 mm diameter holes. The pulse height distributions have been fitted by a Gaussian function determining average amplitude and width values. Using such experimental data, average amplitude and width values have been parameterized as a function of the distances r. Consequently, each point of the YAP:Ce crystal corresponds to a set of three (for the 3 PMT's) or four (for the 2×2 multianode PMT) calculated average amplitude (A_i^{calc}) and sigma (σ_i^{calc}) values. When an alpha-particle hits the YAP:Ce crystal in an unknown point, the measured amplitudes (A_i^{exp}) are compared with the ones calculated for all (x,y) positions. By means of an appropriate reconstructing algorithm, the impact position of the alpha-particle is then reconstructed. This algorithm has been tested for both configurations (3 PMT's and multianode PMT).

A test with a collimator having two crossed 7×1 mm^2 slits placed in front of the YAP:Ce detector has also been performed obtaining the reconstructed positions reported in Figure 4.

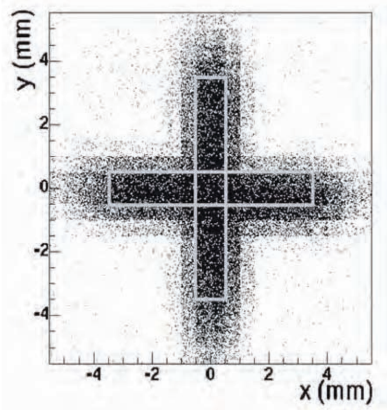

Figure 4. Comparison between the "true" position of the mask with two crossed 7×1 mm^2 slits (grey lines) and the reconstructed one (black dots).

The system with the 4 sector PMT has also been tested at IRB by detecting alpha-gamma coincidences produced in the irradiation of two $5\times5\times5$ cm^3 graphite samples by using a cubic $10\times10\times10$ cm^3 NaI(Tl) scintillator. The tritium target was at 8.8 cm from the YAP:Ce detector and at 88 cm from the plane defined by the two graphite samples. The average distance between the two samples and the center of the NaI(Tl) detector was about 25 cm. The NaI(Tl) was protected from direct neutrons by a heavy metal shadow bar. The position distribution of the alpha-gamma coincidences on the YAP:Ce detector is shown in Figure 5, as obtained by setting windows on the time of flight of the neutrons hitting the graphite samples and on the NaI(Tl) energy corresponding to the 4.4 MeV gamma ray produced by (n,n'γ) reactions on ^{12}C nuclei. Two well defined structures in the reconstructed YAP:Ce (x,y) positions are clearly separated thus providing a direct test of the imaging capability of our prototype. The different yields of the two structures are due to the difference in the solid angles subtended by the two samples with respect to the NaI(Tl) detector.

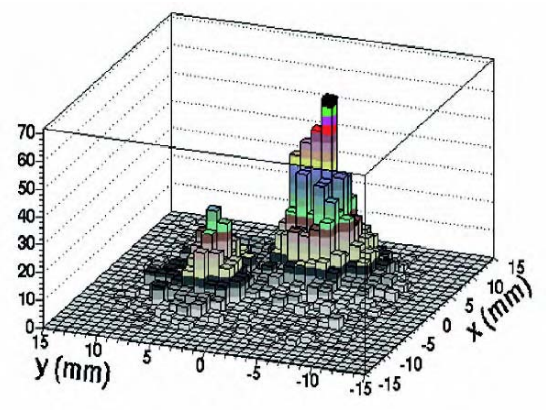

Figure 5. Reconstructed position on the YAP:Ce detector of two graphite samples. For details se the text.

4.2. READ-OUT WITH "THRESHOLD METHOD"

One possible design for a second generation system is based on a matrix of 64 YAP:Ce scintillators. In this case the detector-TiT target distance is increased to 15 cm. This solution would automatically lower the count rate of each YAP:Ce of the matrix compared to the use of a larger single YAP:Ce crystal.

A matrix of YAP:Ce detectors mounted on a stainless steal structure has been tested at the Laboratori Nazionali di Legnaro with a standard ^{241}Am source. The matrix hosts 64 crystals of dimension 5.8×5.8 mm^2, the spacing between crystals being 0.2 mm and the offset of the crystals from the grid

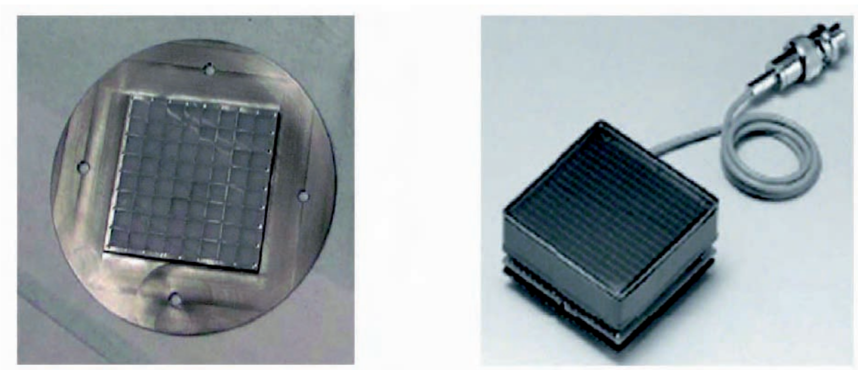

Figure 6. Pictures of the holder with the 64 crystals inserted and of the H8500 PMT.

surface being 0.4 mm. The 64 crystals are coupled to a H8500 PMT through a quartz window of 4.0 mm thickness. No optical coupling has been applied, so that the light transmission is by air-gap.

Figure 6 shows a picture of the holder with the 64 crystals inserted and the H8500 PMT. The geometry of the setup is such that each YAP:Ce crystal is exactly facing one sector of the H8500 PMT. Nevertheless, since the YAP:Ce crystals are not directly coupled to the H8500 PMT but the 4 mm optical window is interposed, the light signals originating from a single crystal diffuse through the window to the adjacent sectors of the PMT.

The scope of the tests was to verify the possibility of identifying the alpha particle hit position by simple threshold discrimination on the output pulse from each PMT sector. To reach this goal, the amplitude distribution of the alpha signals in the whole surface of a single YAP crystal has to be compared with that from the nearest crystals that see the induced light. The differences between the amplitude distributions will directly provide the amount of effective “optical crosstalk” between adjacent elements of the YAP matrix.

The tests were performed by inserting a square mask in front of four different crystals. The alpha source was placed in air at a distance of about 2.3 cm from the crystal surface in order to release in the crystal a reduced energy of about 3 MeV, as in the case of the neutron producing reaction. In Figure 7 are shown the results of the irradiation of the crystals #36, #27, #28 and #35.

In all the amplitude distributions are present contributions from “direct alpha hits” (see the gray region marked for PMT #36 in Figure 7) and from alphas that hit adjacent crystals. The arrows indicate, for each crystal, the peak relative to direct hits.

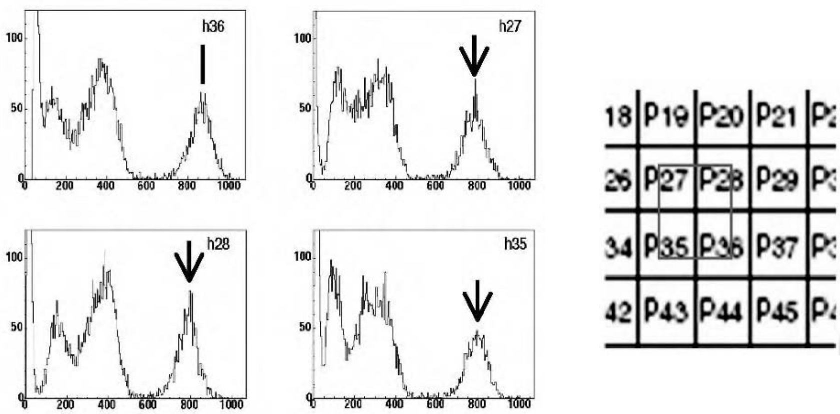

Figure 7. Results of the irradiation of the four crystals #36, #27, #28 and #35.

It is seen that the distribution of signal amplitudes due to direct hits is rather narrow and totally decoupled from the distribution of amplitudes of the induced signal due to the optical cross-talk between crystals due to the presence of the 4 mm quartz window.

In a second step, the effects induced by the use of an energy threshold were studied. In Figure 8 are shown the energy spectra of all the four crystals obtained setting the energy gate on the spectrum #36 indicated by the gray area. As a result, the direct alpha hit structures in the crystals #27, #28 and #35 disappeared completely. This test reflects what should happen in the real operation of the alpha tracker inside the neutron generator by using an energy threshold to eliminate the induced signals: due to the energy difference, the threshold will allow reducing virtually to zero the crosstalk between crystals of the array without loosing tagging efficiency.

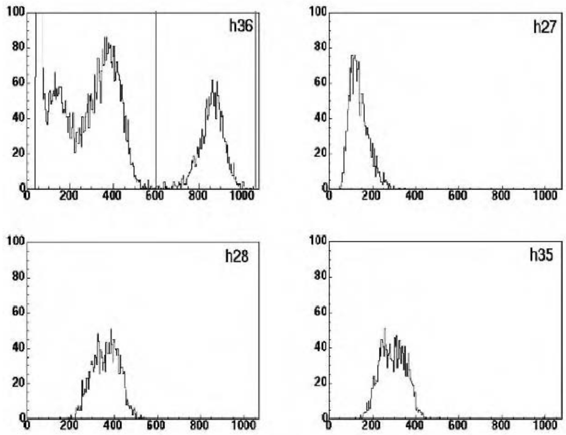

Figure 8. Energy spectra of all the four crystals obtained setting the energy gate on the spectrum #36 indicated by the gray area.

The second generation of TNIS will be used in our current projects on cargo container inspections. The first project is a collaboration between INFN and IRB funded within the NATO Science for Peace programs. Moreover a larger collaboration was recently started including other European Research Institutes and Industries, called EURITRACK (EURopean Illicit Trafficking Countermeasures Kit) which has been approved in the framework of the 6th Framework Program of the European Union.

5. Detection of Hidden Explosive in Vehicles

The techniques involving the detection of gamma rays allow inspecting a volume and obtaining an information on the chemical composition of the irradiated objects thus identifying explosive materials [8,9]. As previously discussed, the use of tagged neutrons improves the performances of such systems allowing a better definition of the voxel [15]. However, because of the low cross sections of (n,n'γ) reactions, the irradiation time needed to obtain useful information with this technique is quite long. As a typical example, 5 minutes are needed for a single inspection with PELAN [21]. Consequently these systems can not be used to perform a fast scanning of extended objects.

The detection of Improvised Explosive Devices is one of mayor tasks in the contrast of terrorist actions. In this respect, a specific case is the inspection of vehicles at check points to prevent attacks with explosive cars against sensitive targets. The quantity of explosive material used in such attacks ranges from 200 kg to several tons. Such large quantity of hydrogen rich material hidden in vehicles can be detected in very short time by looking to the transmitted and scattered neutrons. This technique does not provide precise information about the chemical composition of the voxel, but could be used to make a first level scanning of vehicles.

Detailed GEANT Monte Carlo simulations [22] have been recently performed in the case of a car having explosive hidden in the trunk. We have simulated the TNIS with a 64 pixel matrix embedded into the system. A source of tagged neutrons using both the D+T and the D+D source reactions has been considered. However, the results of the simulations reported here are only relative to the D+T reaction. The car is simulated by a stainless steel and plastic box having dimensions $4.5\times1.8\times1.5$ m^3. The distance between the neutron producing target and the center of the car is 120 cm. In the car we have simulated the presence of a plastic baggage car, a tank filled with fuel, the tires, the front and back seats and the engine.

Tagged neutrons transmitted trough the vehicle are detected in coincidence with the associated particles by using position sensitive neutron detector (N_T) covering an area of 110×110 cm^2. Four large pad detectors (N_{D1}, N_{D2}, N_{D3}, N_{D4}), each having an area of 120 x 50 cm^2, are used to detect scattered neutrons at the road level below the car.

The car and the inspection systems as folded in the Monte Carlo simulations are shown in Figure 9. Each simulation run corresponds to the emission of 8×10^6 neutrons on 4π. To reproduce the scanning of the car, the neutron detectors and the neutron generator were moved along the x axis in steps of 40 cm.

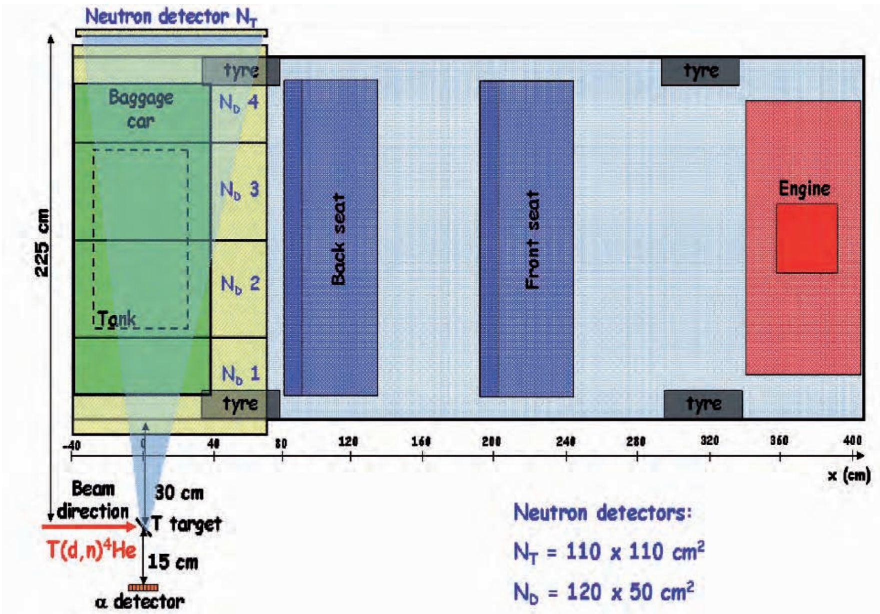

Figure 9. Lay-out of the simulated system with the neutron generator, the car and two neutron detectors.

With the neutron detector placed behind the car we can estimate the attenuation of the neutrons passing through different materials. We define the neutron Attenuation Factor (ATF) as the ratio $(A_{max}-A_i)/A_{max}$, where A_{max} is the maximum number of unperturbed neutrons that are hitting the neutron detector during the scanning of the car and A_i is the number of unperturbed neutrons hitting the neutron detector, when the generator is placed in the position i.

With the neutron detectors placed under the car (N_D) it is possible to estimate the neutrons scattered backwards and forwards. We have defined as Asymmetry Factor (ASF) the ratio $(A_{D1} + A_{D2})/(A_{D3} + A_{D4})$, where A_{Di} are the counts in each N_{Di} neutron detector pad.

Both the observables, ATF and ASF, are used to discriminate the presence of light Z material, as the explosive, from other thick absorbers, as the vehicle engine.

In the left panel of Figure 10 we have reported the value of the neutron Attenuation Factor as a function of the neutron generator position. Two regions with a strong attenuation are identified, which correspond to the scanning of the trunk and of the engine.

The values of the Asymmetry Factor as a function of the neutron generator position are shown in the right panel of Figure 10. The Asymmetry Factor varies generally in the range from 0. to 1.5 for all

positions with the exception of the trunk filled with TNT where it is much larger.

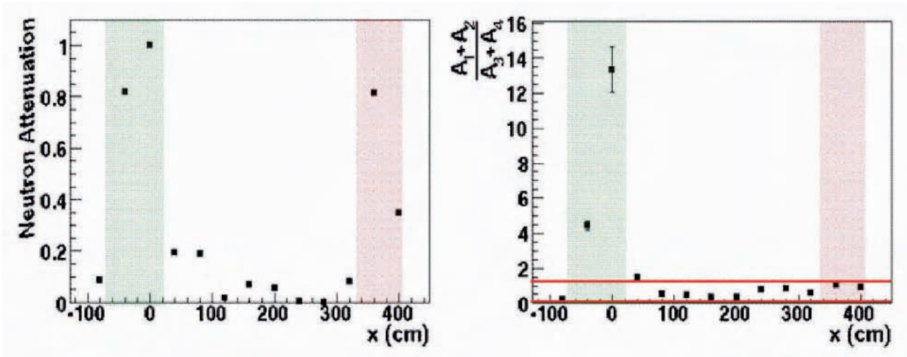

Figure 10. Left panel: Neutron Attenuation Factor as a function of the neutron generator position. Right panel: Asymmetry Factor as a function of the neutron generator position. For details see the text

Moreover, a number of simulations have been performed, by changing the dimensions of the TNT sample placed at the centre of the trunk. The sample was always 40×40 cm^2 in the x and z dimensions whereas its depth was varied from 0 to 150 cm in the y dimension.

In the left panels of Figure 11 the Neutron Attenuation Factor is reported as a function of the weight of the TNT hidden in the trunk. The plot in the upper panel is obtained selecting all the pixels of the tagging detector (wide beam), while the one in the lower panel is obtained selecting only the pixels that are defining the neutron beams investigating the sample (narrow beam). It is seen that the inspection with narrow beam provides more precise information on the hidden explosive. Moreover, in the right panel the values of the Asymmetry Factor are also reported as a function of the explosive weight. It is seen that when the explosive is more than 150 kg, the value of the asymmetry is grater than the value obtained for the average content of the car providing a good explosive discrimination. This fact suggests that the minimum quantity of explosive detectable with this method is about 150 kg.

Some important considerations have to be done on the counting rates obtained with our set-up and on the dose equivalent absorbed by a driver passing through the scanning system.

As already discussed, each simulation corresponds to the emission of 8×10^6 neutrons on 4π. If we suppose to have

- a 14 MeV neutron generator emitting 8×10^7 neutron/s,
- neutron detectors with an efficiency of about 10% for 14 MeV neutrons,
- a shielded neutron source,

with our geometry we will have a rate of 640k tagged neutron/s, 57k neutron/s detected by the N_T detector in the case of an empty vehicle and 1.4k neutron/s detected by each segment of the N_D detector. The count rate estimate for the scintillation detectors indicates that there is no need to use special electronics.

Under the above conditions and considering a distance between the driver and the neutron producing target of about 50 cm, the driver will receive a dose equivalent of about 0.8 microSv/s [23], when directly exposed to neutrons. Consequently, if the scanning time of the car is of the order of 10 s, the driver will be exposed to the neutron flux for about 3 s, which corresponds to a dose of about 2.5 microSv. This value is 400 times lower than the Italian annual allowed dose for not-exposed workers.

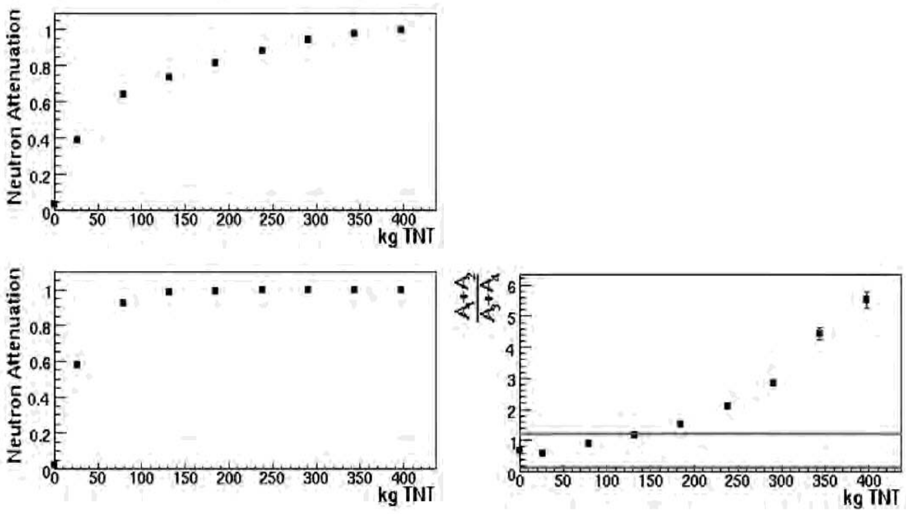

Figure 11. Neutron Attenuation Factor and Asymmetry Factor as a function of the weight of the explosive. For details see the text.

6. Conclusions

The use of tagged neutron beams to search for hidden explosives is one of the available technology that might in future be used to implement the existing tools (as the X-ray scanners). The derived information is highly specific in the case of the gamma ray spectra induced by fast neutrons and allows the elemental analysis of the inspected voxels. Alternatively, fast neutron transmission and scattering measurements can be used to perform fast scan of suspect vehicles.

Acknowledgements

This work is part of the programs "Control of illicit trafficking of threat materials" funded by the NATO Science Programme under the grant SfP - 980526 and EURITRACK (EURopean Illicit Trafficking Countermeasures Kit) Project funded by European Union within the 6th Framework Program.

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SENNA – PORTABLE SENSOR FOR EXPLOSIVES DETECTION BASED ON NANOSECOND NEUTRON ANALYSIS

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Abstract. Prototype portable device for detection of concealed explosive and other hazardous substances has been created on the basis of a neutron generator with built in position-sensitive detector of α-particles. Secondary γ-rays produced in the investigated volume by incident fast neutrons are detected in narrow (few nanoseconds) time interval counted from the moment of detection of the alpha particle, that had accompanied emission of neutron from the generator (Nanosecond Neutron Analysis / Associated Particles Technique NNA/APT). Analysis of the spectra of γ-rays allows one to determine elemental composition of the substances located in the investigated volume. Use of a position-sensitive tagging α-particle detector allows one to determine the flight direction of each neutron, and thus to divide the investigated volume into "voxels" producing its 3D "elemental" image.

1. Introduction

One of the most promising methods of detection of concealed explosive and other hazardous substances is the so-called, "neutron in, gamma out" technique. The main idea of this method consists in irradiation of the suspicious object or volume with neutrons and measurement of secondary γ-quanta, which is caused by reactions between neutrons and the material of the object. Various chemical elements produce characteristic γ-radiation as a result of scattering and capturing of neutrons. By decomposing the measured γ-spectra into contributions from different chemical elements, it

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H. Schubert and A. Kuznetsov (eds.) Detection and Disposal of Improvised Explosives, 87–96.

is possible to obtain elemental composition of the investigated object and thus to determine whether it contains explosive substances (ES) or not.

The most important advantage of "neutron in, gamma out" methods is that neutrons and high energy γ-quanta have very high penetrating ability, and explosives can be detected even if they are hidden under thick layers of soil, concrete, or behind metallic or other barriers.

Efforts to develop devices based on "neutron in, gamma out" methods were made since 1970s in several countries. While some variations of this method (for example, Thermal Neutron Analysis – TNA; Pulsed Fast Neutron Analysis – (P)FNA) are at present successfully applied in specific detection scenarios, a wide application of this potentially very powerful and universal method is hindered by a number of remaining unresolved issues [1].

The most important of them is that small quantities of explosives may be hidden inside large volume of "parasitic" material, so that the contribution from this material to the measured γ-ray spectrum (background) may considerably exceed the effect from the explosive substance. This leads either to the increase of the time needed for detection, or to the impossibility to extract the effect from the “noisy” spectrum.

2. Nanosecond Neutron Analysis / Associated Particle Technique (NNA/APT)

Nanosecond Neutron Analysis (NNA) [2,3] is a variation of the Associated Particle Technique (APT) [4], which relies on detection of secondary γ-rays, produced in the investigated volume by fast neutrons, within narrow (few nanoseconds) time intervals counted from the moment of emission of the “tagging” associated particle. By suppressing the background component of γ-spectra, NNA/APT significantly reduces the detection time of concealed hazardous substances.

The time between the moment of emission of the neutron from the neutron source and arrival of the secondary γ-quantum, produced by this neutron in the investigated material, to the detector is determined by the time of flight of the neutron from the source to the point of interaction with the substance, plus a small addition due to time of flight of the γ-quantum (which travels at speed of light) from the point of interaction to the detector $t = \tau_n^{(\text{source-substance})} + \tau_\gamma^{(\text{substance-detector})}$. This time, which thus mostly depends on the distance to the investigated object and the velocity spectrum of neutrons, is in the range from several nanoseconds up to tens of nanoseconds (1 nanosecond = 10^{-9}s). All γ-quanta that are connected with reactions of inelastic scattering of fast neutrons in the material of the investigated volume must arrive in the detector within this narrow time

window, and γ-quanta from other sources are not correlated in time with the moment of emission of neutrons from the neutron generator.

The best sources of neutrons for the elemental analysis by "neutron in, gamma out" methods are portable neutron generators. They can provide sufficient fluxes of fast neutrons, while not producing any ionizing radiation when switched off.

Portable neutron generators (NG) are commercially available from several producers, such as EADS/SODERN, Thermal MF-Physics, All-Russian Research Institute of Automatics – VNIIA. One example of using neutron generator in the device for detection of explosives is PELAN created at University of Kentucky, USA, and marketed by SAIC[1].

When a portable neutron generator is equipped with a position-sensitive α-particle detector, which detects α-particles from $d+t \rightarrow \alpha+n$ reaction, each detected α-particle "tags" the corresponding neutron, so that its direction and time of emission are known. The principle is illustrated on Figure 1.

3. SENNA –Portable Device for Detection of Explosive and Other Hazardous Substances

NNA/APT has been implemented in a portable single-case remotely controlled SENNA (see photo at Figure 2).

SENNA is based on portable neutron generator NG27 with 3×3 matrix of 1 cm^2 α-detectors, two γ-ray detectors based on BGO crystals and electronics, which combines data acquisition, data analysis and control functions.

3.1. NEUTRON GENERATOR NG27

Neutron generator NG27 produced by VNIIA, Moscow, is equipped with a 3×3 matrix of 1cm^2 semiconductor α-detectors produced by APSTEC, St.-Petersburg[2]. The maximal intensity of the NG27 is 5×10^7 n/s, about 2% of which are tagged by the multi-segment α-detector (in the current version). Unlike scintillator-based α-detectors, the semiconductor α-detector used in SENNA has 100% intrinsic detection efficiency for ~3 MeV α-particles. The fast on-board electronics provides on-line information about time of detection of each α-particle and the number of the hit segment.

[1] For information about commercial neutron generators see web sites of producers, as well as article by O. Bochkarev in this volume.

[2] For more information about NG27 and associated particle detectors see web sites of producers: www.vniia.ru and www.apstec.ru.

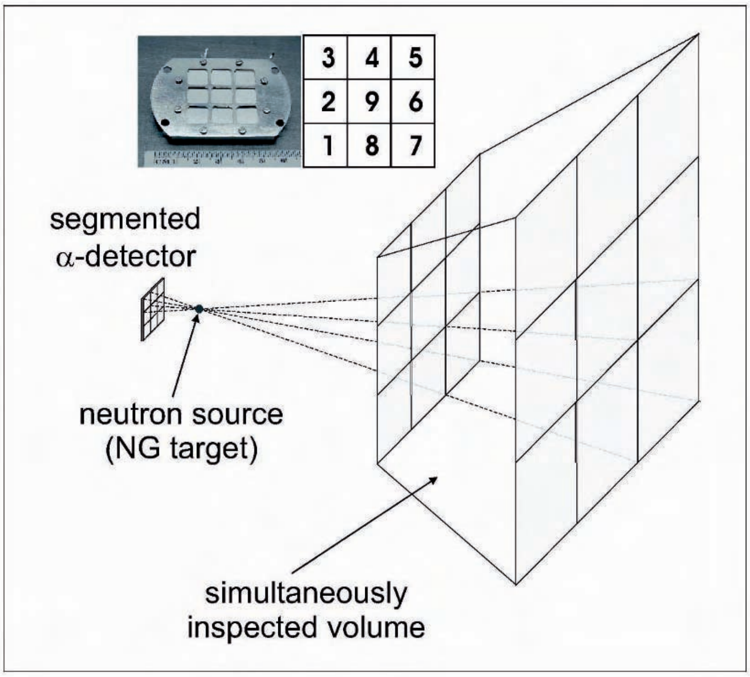

Figure 1. Principle behind Nanosecond Neutron Analysis / Associated Particle Technique.

Figure 2. SENNA inspecting a suitcase.

Other types of α-detectors and neutron generators are currently available from the respective producers, varying in the geometrical efficiency of the α-detector and its segmentation.

3.2. DETECTORS

SENNA currently uses two γ-ray detectors based on $\varnothing 6.3\times 6.3$ cm^3 BGO crystals and R6233-01 Hamamatsu photo multipliers. BGO crystals were selected for having high efficiency at small size, which is an important feature for a portable system. Having small crystals reduces the weight of any additional shielding of the crystal volumes from the direct neutron flux. Since the BGO crystals are outside the pseudo-beam of "tagged" neutrons, the primary neutrons hitting the crystals are not accepted by the DAQ, so the device can be used without shielding.

The selected photo multiplier retains good characteristics at high load. Detectors have energy resolution better than 10% for 0.66 MeV ^{137}Cs line.

3.3. ELECTRONICS

The task of SENNA's data acquisition system (DAQ) is to provide energy and time-of-arrival relative to the tagging α-particle for each detected γ-quantum. It must work at extremely high counting rates: up to 10^7 α/s in the α-detection channel and up to 10^6 γ/s in each γ-detection channel – if this electronics is to survive the planned future upgrades of SENNA.

The DAQ uses modular approach. One module services the multi-segment α-detector, providing time-of-arrival for each α-particle relative to the internal clock, and making this information, together with the number of the hit segment, available to other blocks via a dedicated bus. Other modules, one for each γ-ray detector, are based on fast ADC, whose output is analyzed on-line by a dedicated programmable logic device (PLD) and digital signal processor (DSP). As a result, energy and time-of-arrival of each γ-quantum are determined, and then correlated with the available information about the α-particle. The resulting energy and time-of-flight for each γ-quantum are stored in buffer memory of each block, and are transferred to the analyzing PC on demand.

DAQ achieves record-high time resolution for BGO-based spectroscopic γ-detectors – better than ~1.5 ns, and preserves energy resolution at counting rates over 10^6 γ/s per detector.

A single-board computer is integrated into the electronics and performs data analysis and control functions: analyzing collected spectra, setting all high voltages on γ-ray and α-particle detectors, setting parameters of signal processing and data acquisition mode, etc.

3.4. DATA ANALYSIS AND DECISION-MAKING

SENNA Performs Data Analysis in Several Stages:

- Constructing energy spectra of γ-quanta for all "voxels" of the sensitive area from the event-by-event raw data file. Since light output of BGO crystals depends rather steeply on temperature, automatic energy calibration is performed for each newly collected spectrum.
- Determining concentrations of key elements by partial least squares (PLS) and Principle Component Analysis (PCA) algorithm [5] – typically about 10 chemical elements are simultaneously used in the data fitting.
- Decision-making by "fuzzy logic" mechanism.

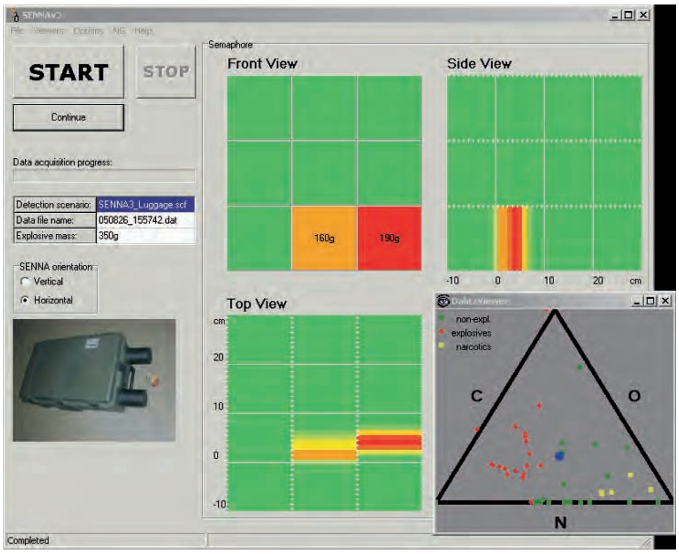

Figure 3. SENNA program window.

SENNA's automatic "fuzzy logic" (FL) decision-making procedure is based on detection scenarios. FL "scans" the sensitive area in-plane and in-depth, and analyses concentrations of key chemical elements obtained by the PLS algorithm for each "voxel". It then decides whether there is an explosive or not, where exactly, and how much. If no definite decision can be made due to low statistics, FL automatically prolongs measurements.

Scenarios determine, among other things, the role of individual chemical elements in the decision-making: e.g. carbon detected inside a concrete wall is an important indicator of ES presence, while the same

amount of carbon inside a suitcase may be due to some "innocent" material like clothing or a stack of magazines.

Example of the SENNA program window indicating presence of threat objects in two red "voxels" in the inspected volume is shown at Figure 3.

Apart from showing the position of the threat object, the analysis software also provides the operator with the estimated mass of the threat object.

3.5. EXPERIMENTAL RESULTS

SENNA has been tested in the following detection scenarios:

1. inspection of small isolated objects (e.g. a suspicious object left in public place);
2. inspection of suitcases filled with common luggage articles;
3. inspection of small boxes and containers.

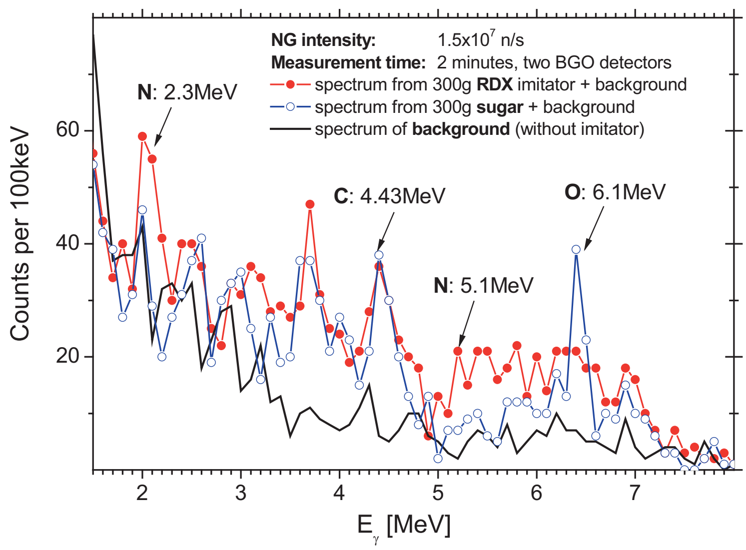

Figure 4. Experimental spectra for RDX imitator, sugar, and the experimental background.

3.5.1. *Inspection of a Small Isolated Objects*

In order to speed up and simplify measurements, imitators of explosives were used. An imitator suitable for NNA/APT must have the same relative concentrations of carbon, nitrogen and oxygen (C, N, O) as the real explosive. Mixtures of inert substances imitating chemical composition of RDX, TNT, C4, PETN etc. were sealed inside metallic Cola cans. Some

cans contained inert materials (e.g. sugar, water, cola…) Weight of all imitators was 300 g.

Examples of experimental spectra obtained for imitator of RDX, for sugar and the background (without imitators) are shown at Figure 4.

While both RDX and sugar contain carbon and oxygen, only RDX contains nitrogen, which contributes to the γ-ray spectrum in the region around 2.3 MeV and around 5.1 MeV.

3.5.2. *Inspection of Suitcases*

In another series of experiments explosives' imitators weighting from 300 g to 1 kg were placed into a suitcase filled with common luggage articles: cotton and woolen clothing, books, CD cases, water, soap, vodka etc.

Even in such complex filling the recognition procedure successfully determined presence of explosives in some "voxels", while showing no alarms in other "voxels", or when the explosive' imitator was replaced by an inert object, such as 1 kg of sugar (see example of the filling on Figure 5).

Figure 5. Example of the suitcase filling and the alarm given by SENNA to the 1 kg TNT imitator located under two pieces of soap.

3.5.3. *Inspection of Small Boxes and Containers*

SENNA was also successfully used to detect 1 kg of explosives' imitator hidden inside a box with 36 packs of washing powder, and 1 kg of melamine (with high nitrogen content) inside a small container filled with luggage items. In the latter case the imitator was buried at depth of ~50 cm inside the container. Example of the obtained distribution of carbon, oxygen and nitrogen along the in-depth coordinate of the container is shown at Figure 6.

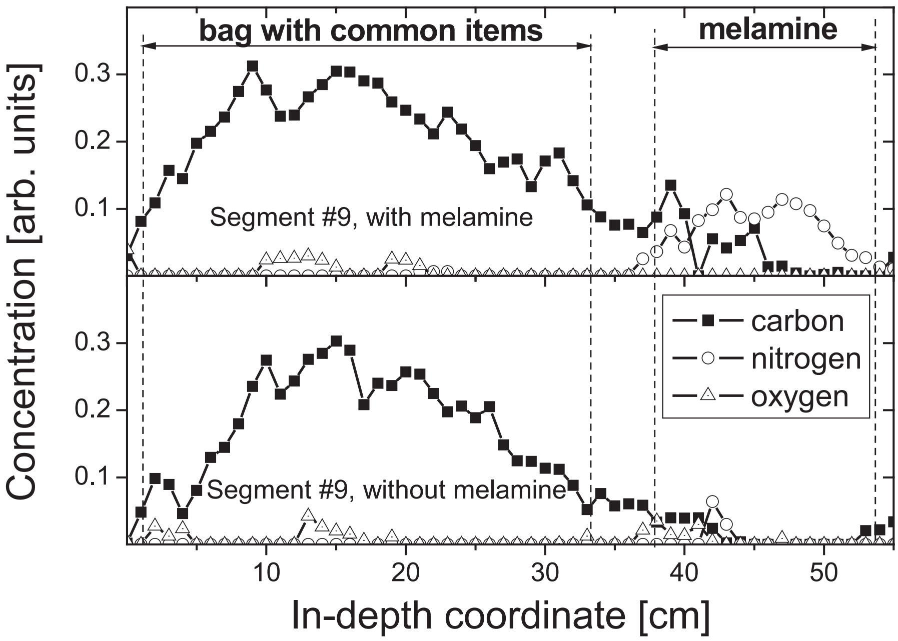

Figure 6. Distribution of nitrogen, carbon and oxygen along the in-depth coordinate of the container.

An increase in the amount of nitrogen between 40 cm and 50 cm is due to the presence of melamine.

4. Conclusions

SENNA is a fully functional portable device for detection of concealed bulk explosives and other hazardous materials. It is based on Nanosecond Neutron Analysis (NNA) and advanced decision-making algorithm.

SENNA decision-making procedure is scenario-driven. Whatever the difference in elemental composition of the detected explosive from that of the inert substances, it can be used for detection.

SENNA can be scaled up to increase the simultaneously inspected volume and further reduce the detection time.

Acknowledgements

This work was supported in part by the CRDF, USA, grant RP2-564, and in part by APSTEC Co Ltd., Russia.

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LIQUID BLAST INHIBITORS: TECHNOLOGY AND APPLICATION

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Transportation systems are the most vulnerable targets for terrorist attacks. Analysis of the available data based on the results of the 25th International Conference "Civil Aviation Security" has shown the rise of terrorism in the Russian Federation, especially directed at air transportation. Thus, in 1997 32 acts of terrorism were recorded, in 1998 – 21, in 1999 – 20, in 2000 – 135, in 2001 – 327, in 2002 – more than 330, i.e. 10 times as much as seven years ago. The most urgent task is equipping airports with innovative passenger and luggage examination equipment. However, such equipment cannot exclude by 100% possibility of smuggling explosives on board of an airplane. Danger is presented not only by large amounts of explosives, but also by small-size explosives (less than 100 g) that are able to disperse poisoning reagents in an airplane cabin and by midsize explosives (200 g – 2 kg) that are able to destroy an airplane fuselage. For example, a 200 g TNT explosion in the plane tail-end that is near the engine may results in either the tail-end break away (TU-134) or massive fracture of the airplane (TU-154). Thus, it is important to be ready to eliminate blast effects caused by various amounts of explosives.

At present a wide range of protective devices [1] designed for isolating and mitigating harmful blast effects are known, such as anti-fragmentation blankets, blast protection containers [2], and liquid blast inhibitors.

Liquid blast inhibitors [1] significantly attenuate blast damage effects and can be considered as very promising for wide application because of favorable combination of high protective properties and safe usage. Liquid blast inhibitors are containers composed of several elastic envelopes. The shape of the container allows complete isolation of the suspicious object. In case of an explosion, considerable part of the blast energy is spent on the

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container deformation and its destruction. This occurs without secondary fragmentation.

A family of liquid blast inhibitors “Fountain” (Figure 1) are developed and commercially produced by the Research and Production Company “Special Materials ltd.” (St. Petersburg) [3], [4], [5], [6].

Figure 1. “Fountain” blast inhibitors commercially produced by NPO “Special Materials ltd.”

“Fountain” blast inhibitors are designed to mitigate blast damage effects including fragmentation absorption, blast wave and thermal effect suppression. The basic feature of a “Fountain’ device is special emulsion – working medium [7] filling the container. This working medium has high energy-absorption capability, which ensures portability of the device. Fast blast wave attenuation and its plateau along with the blast energy dissipation by the multiphase gas-liquid medium is called Gelfand-Silnikov effect [8].

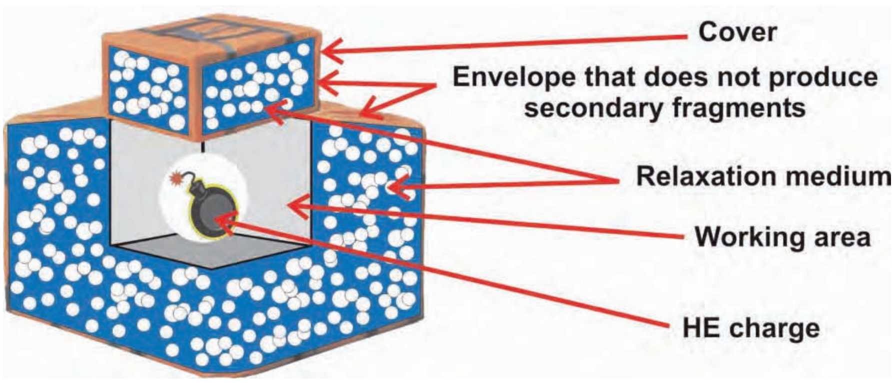

Figure 2. Cross-section diagram of “Fountain 3MK.”

One of the latest developments of NPO SM is “Fountain 3MK” – a blast inhibitor designed for protection against explosives onboard airplanes. “Fountain 3MK” mitigates blast overpressure, fragmentation and thermal

effects caused by HE up to 500 g in TNT equivalent. This inhibitor is a monoblock unit shaped as a cube filled with liquid working medium. (Figure 2). The total weight without the cover is 70 kg. From the outside the unit is equipped with an anti-fragmentation screen made of aramid fibers. A suspicious object found onboard airplane is to be placed inside the working area. Afterwards the device has to be closed by the cover. The working area is 310 mm wide and 220 mm high.

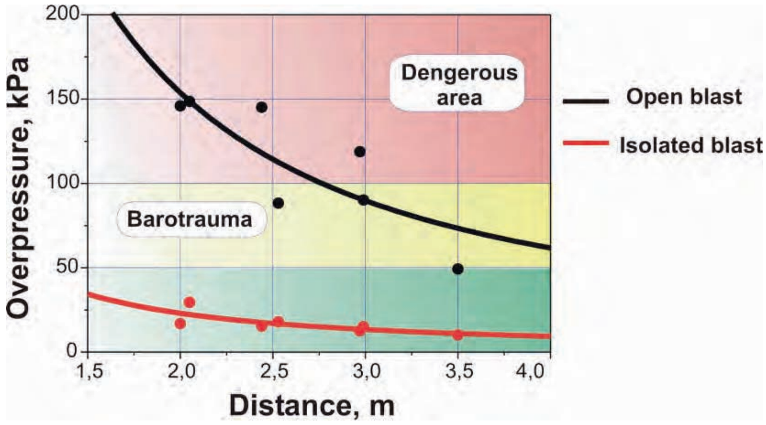

Figure 3. Overpressure in case of 0.5 kg TNT open explosion and isolated by “Fountain 3MK”. 50 kPa and 100 kPa levels indicate the barotrauma threshold and the dangerous area correspondingly [9], [10].

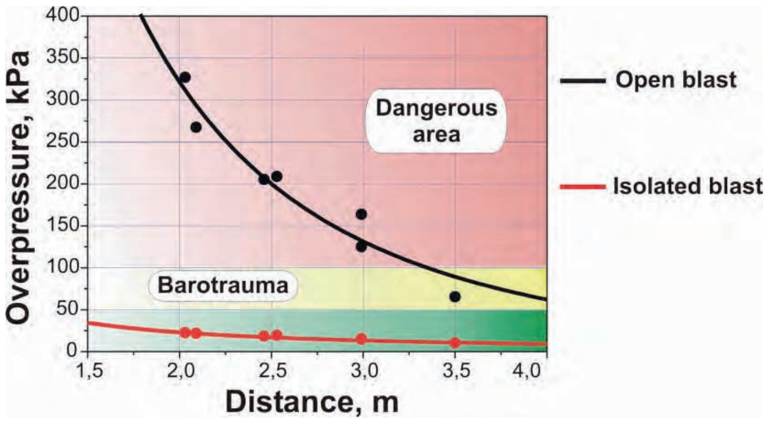

Figure 4. Overpressure in case of 1 kg TNT open explosion and isolated by “Fountain 3MK.”

To verify blast protection efficiency of “Fountain 3MK” a number of tests has been performed. Shock wave overpressure was measured as a parameter of the blast effect. The overpressure dependences on the distance

obtained in tests with 0.5 kg TNT and 1 kg TNT charges are presented on Figures 3 and 4. The diagrams show that the blast inhibitor significantly reduces the radius of the dangerous area (P > 100 kPa). The barotrauma threshold corresponds to 50 kPa [9], [10].

It should be noted that during the tests the HE charges were placed on the thick armor plate. Blasts on solid surfaces differ from those in the air, due to complete reflection of the blast wave and, as a result, doubling of the wave peak. Explosion onboard airplane is better approximated by an air explosion than by the ground explosion. Nevertheless, the overpressure results obtained at the ground tests of the inhibitor at 1.5 m distance from the epicenter turns to be lower than the barotrauma threshold.

Realistic tests of the "Fountain 3MK" on board an airplane IL-96 have been performed. Experts from ZAO "S.V. Iliushin Aviation Complex" took part in the tests. To install the "Fountain 3MK" a pass-through hatch was made in the tail-end of the plane (Figure 5). The inhibitor was fixed in the cargo compartment directly under the hatch. If a suspicious object is found on board, it should be placed inside the working area of the inhibitor, after that the inhibitor is covered with the top from the passenger cabin side.

Figure 5. Location of the blast inhibitor 'Fountain 3MK" on board IL-96.

An air shock wave overpressure resulted from 500 g TNT explosion was considered as a characteristic of the blast inhibitor protective properties. The air shock wave pressure was recorded with piezoelectric detectors according to the technique developed in NPO SM [11].

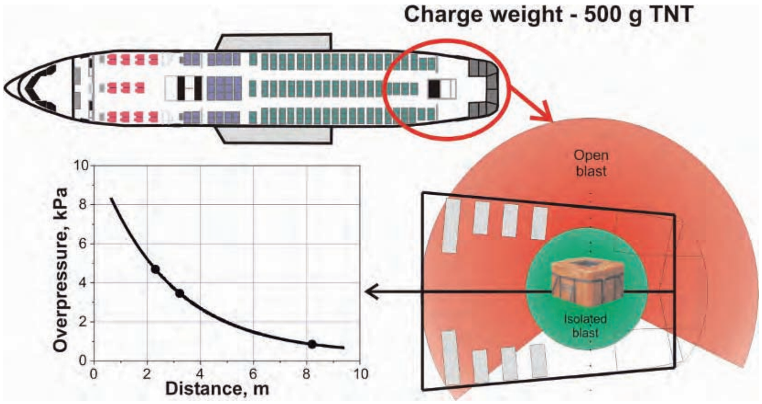

Figure 6. Dangerous overpressure area at the open and isolated 500 g TNT detonations. The overpressure dependence on the distance in the direction from the epicenter to the airplane axis of symmetry in case of the isolated explosion.

Figure 6 shows dangerous area for open 500 g TNT detonation and for isolated by "Fountain 3MK" 500 g TNT detonation. The overpressure dependence on the distance in case of the isolated explosion is shown in the direction of the airplane axis of symmetry. A diagram on Figure 6 shows that the shock wave attenuates in time. Thus, shock tube effect at which shock wave propagation becomes stationary is not observed. Typical shock wave profiles in the passenger cabin are given on Figure 7.

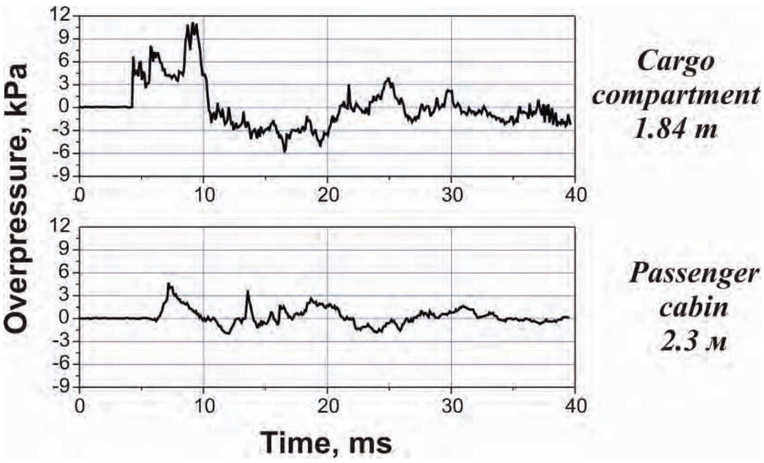

Figure 7. Shock wave profiles in the cargo compartment (1.84 m from the epicenter) and in the passenger cabin (2.3 m from the epicenter).

It should be noted that the incident wave in the cargo compartment had a sharp front, i.e. it was a shock wave, but in the passenger cabin the incident wave front was not that sharp, with low peaks. It should be rather considered a strong acoustic wave than a shock wave. Thus, at the given location of the blast inhibitor, the main blast energy is directed to the cargo compartment.

For the visual observation of the explosion process a video camera was installed in the passenger cabin at 14 m from the epicenter (Fig. 8).

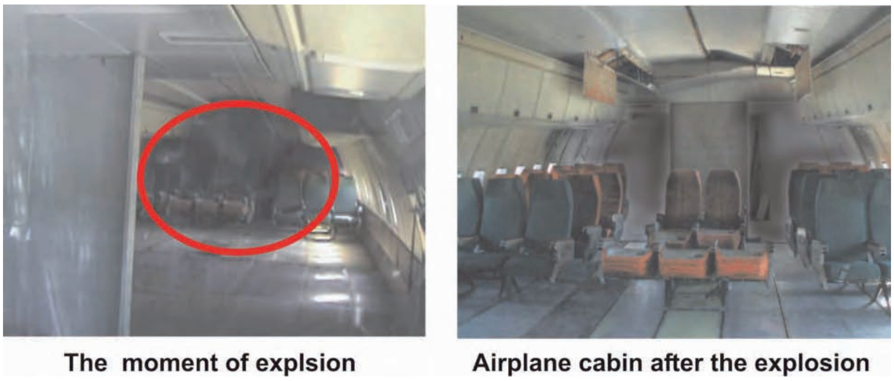

Figure 8. 500 g TNT explosion isolated by 'Fountain 3MK" on board IL-96.

Figure 8 shows that the isolated explosion has resulted in insignificant damage of interior paneling; passenger chairs were not moved.

Thus, at the given location of the blast inhibitor on broad IL-96 the highest level of the shock wave overpressure resulted from isolated 500 g TNT explosion was recorded in the range of 25-30 kPa in the cargo compartment directly under the inhibitor in the lower part of the compartment. In the passenger cabin the overpressure did not exceed 5 kPa at 2 m distance from the epicenter. While the shock wave was propagating along the passenger cabin it was attenuating. Experts from ZAO "S.V. Iliushin Aviation Complex" came to the conclusion that destruction in the passenger cabin and cargo compartment caused by isolated 500 g TNT was local and did not reduce the flying ability of the IL-96 airplane.

The fight against terrorism is a complex problem. It is necessary to have a wide range of equipment and to have a possibility to choose the most suitable device for the given case. It is important to have a range of liquid blast inhibitors of the "Fountain" type among such equipment.

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RATIONAL DETECTION SCHEMES FOR TATP NATO ADVANCED RESEARCH WORKSHOP

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Abstract. Detection of improvised explosives such as triacetonetriperoxide (TATP) requires detailed knowledge of its chemical and physical properties. Electronic structure calculations were employed to study the properties of the explosives TATP and diacetonediperoxide (DADP). The calculated results were compared to available experimental data. The lowest energy structure, vibrational spectrum and thermal decomposition mechanism of TATP were examined. The applicability of these theoretical methods was demonstrated by the agreement between the experimental data and the calculated ground state structure as well as the vibrational IR and Raman spectra. The thermal decomposition pathway of a TATP molecule was investigated by a series of calculations aimed to identify the transition states along the decomposition pathway, the associated intermediate fragments and the final decomposition products. The initial chemical events that take place during detonation of bulk triacetonetriperoxide were studied by additional calculations were based on molecular dynamics (MD) simulations. In these simulations a reactive force field was used, which has been extended to reproduce the quantum mechanics (QM)-derived relative energies of the reactants, products, intermediates and transition states related to the TATP unimolecular decomposition.

Keywords: Improvised explosives, triacetone-triperoxide. molecular dynamics, remote detection

1. Introduction

Perodixe-based explosives, including triacetonetriperoxide and diacetone-diperodixe (DADP) have not been used extensively in civilian or military applications due to their low chemical stability, high sensitivity to mechanical impact, and high volatility. Unfortunately the straightforward synthesis of these materials from readily available materials made them popular components of improvised explosive devices by terrorists

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worldwide. As such, there is a great demand for analytical methodology capable of detecting these materials. To develop such methodology an improved understanding of the initial chemical events leading to the detonation of these materials is critical in particular when remote detection is desired. The explosive nature of these materials hampers a detailed experimental study of these initiation steps, hence, experimental observations on peroxide-based materials are limited mainly to analysis of post-blast residues or thermal decomposition studies. The alternative is to employ first principles computational simulation tools suitable for studying these initiation events.

TATP is one of the most sensitive explosives known, a property that allows its use as both primary explosive and the main charge. With power close to that of TNT it has been employed in many explosive devices. However, due to its low chemical stability, high sensitivity to mechanical impact and open flame, as well as its high volatility TATP has not been exploited yet for either civilian or military applications. Unlike most conventional explosive devices, those made of TATP contain neither nitro groups nor metallic elements, making its detection by standard methods quite difficult. Furthermore, TATP, which has a quite unsuspicious appearance, reminiscent of white sugar, has no significant UV-vis or fluorescence spectra.

On the basis of a computational study of the thermal decomposition pathways of TATP, we found that the detonation of this compound is not a thermochemically highly favored event. It is rather drived by an entropy burst, which result in formation of 4 gas-phase molecules from each TATP molecule in the solid state. Thus, the three isopropylidene units and the six oxygen atoms in the molecule do not play the roles of fuel and oxidant, respectively. Contrary to what is expected, the isopropylidene units play merely the role of a molecular scaffold that holds the three peroxide units in close spatial proximity and appropriate orientation for a chain reaction. This structural organization of the TATP ring allows for an efficient cascade of mechanistic events initiated by the homolytic cleavage of one peroxide bond with consecutive cleavage of the adjacent C-O and O-O bonds in the same molecule followed by initiation of neighboring molecules in the condensed phase.

Calculation of TATP molecular properties constitute the basis of further experimental studies aimed at finding improved detection schemes. Spectroscopic methods are the best candidates for the purpose of remote detection.

2. Calculations and Results

The objective of the calculations was to obtain a high degree of accuracy in geometries, binding energies, vibrational frequencies and transition states. Hence, the calculations were carried out using the density functional theory (DFT)-based method as implemented in the Gaussian 98 code package with an appropriate basis set. The accuracy of the method was established by calculating the ground state properties of the TATP and DADP molecules. The calculated geometries were compared to data obtained from X-ray crystallographic data. The good agreement between the calculated and experimental results is noteworthy considering the fact that the calculation was performed on an isolated molecule in the gas phase, while the experimental data correspond to solid-state structure. This agreement suggests that the intrermolecular forces in the solid phase are too weak to cause any significant alteration of the molecular geometry. Figure 1 shows some examples of calculated structure of peroxide based explosives.

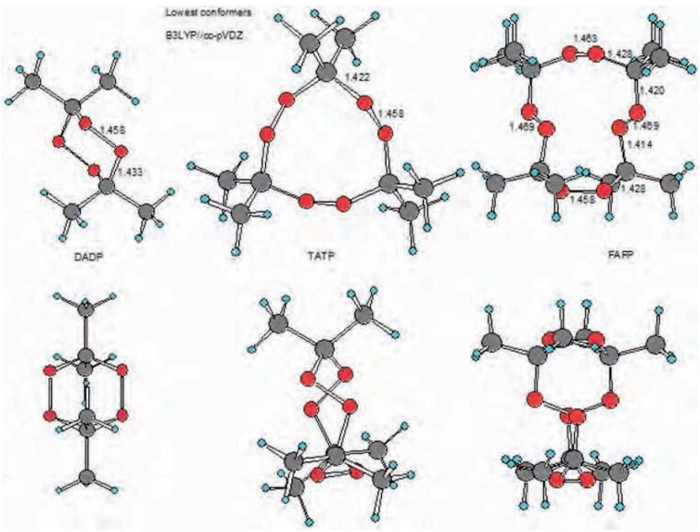

Figure 1. Top (upper row) and side views of the lowest energy configurations of the molecules: DADP (left), TATP (center) and Tetra-acetonetetraperoxide (FAFP) (right) obtained by electronic structure calculation.

Electronic structure calculations were used to study the Lewis acid promoted decomposition of TATP (Dubnikova et. al 2002). The metal ions studied included Fe^{2+}, Al^{3+}, Li^{+}, Cu^{+}, Zn^{2+}, Cd^{2+}, In^{3+}, Sb^{3+}, Sc^{3+} and Ti^{4+}, see figure 2. The calculations yielded a detailed picture of the structure and conformation of the free TATP molecule and of its complexes with the

metal ion. Among all of the metal ions studied, the largest binding energy was found between TATP and In^{3+}. Furthermore, these calculations predicted that the complex formed between TATP and either Al^{3+}, Sb^{3+} or Ti^{4+} would result in ring opening by heterolytic cleavage of a C-O bond, in analogy to the known Lewis-acid-catalyzed cleavage of ketals, to produce three molecules of dimethyldioxacyclopropane that were still coordinated to the metal cation. These complexes are examples of a very rich chemistry which is in good analogy to the chemistry of crown eitheres.

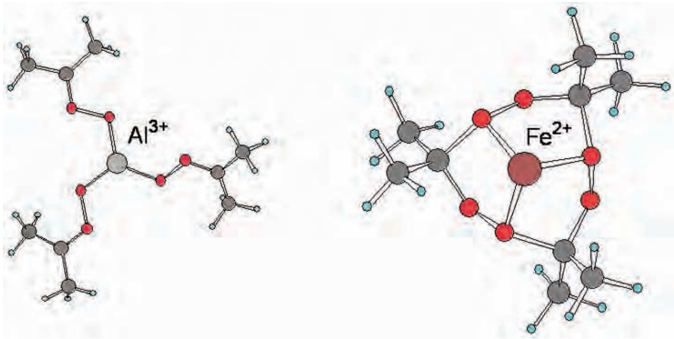

Figure 2. A calculated structure of a complex of TATP with Fe^{2+} and Al^{3+}.

The low bond energy of the O-O bond renders peroxide containing molecules, including TATP heat and shock sensitive. It is expected that the thermal decomposition of these compounds is initiated by homolytic dissociation of the peroxide bond. Intuitively, it is expected that the peroxide based explosives would liberate much energy upon decomposition and their energy content would depend upon their carbon/oxygen ratio. Recent studies of the thermal decomposition of TATP in solution at 151-230 ˚C revealed that this is a first order reaction, exhibiting an Arrhenius dependence on temperature with activation energy of 36.3 kcal/mole and pre-exponential constant of 3.75×10^{13} s^{-1}. The major decomposition products were found to be acetone and carbon dioxide while the minor products included ethane, methanol, 2-butanone and methyl acetate. Product ratio was found to depend on the decomposition temperature. Our calculations show that the thermal decomposition of TATP is an intricate, multi-step and multi-rout process that starts with the dissociation of one of the O-O bonds. Analysis of the total reaction scheme shows that the initial O-O bond cleavage in TATP is the rate-determining step (Dubnikova et. al 2005). The products of this initial step can be obtained via two main pathways with slightly different energy barriers and activation enthalpies. The calculated values of these activation enthalpies and entropies were used

to estimate the Arrhenius parameters for TATP thermal decomposition. The calculated Arrhenius parameters are (Dubnikova et al. 2005):

$$k_1 = 5.47\times10^{16}\exp(-36.35\times10^3/RT)\ \mathrm{s}^{-1}\ \text{(stepwise mechanism)}$$

$$k_2 = 5.88\times10^{16}\exp(-38.82\times10^3/RT)\ \mathrm{s}^{-1}\ \text{(concerted mechanism)}$$

$$k_3 = 5.20\times10^{14}\exp(-36.80\times10^3/RT)\ \mathrm{s}^{-1}\ \text{(reaction via TS3),}$$

where R is given in units of cal/(K*mol). These rates are comparable with the experimental value:

$$k = 3.75\times10^{13}\exp(-36.09\times10^3/RT)\ \mathrm{s}^{-1}\ \text{(experimental)}$$

In order for TATP to sustain an explosive shockwave, the rate of decomposition must match the velocity of the detonation wave. Preliminary molecular dynamics MD calculations have calculated a shockwave velocity of approximately 5400 m/sec.

Assuming that the shockwave velocity in TATP is approximately 5000 m/sec and that the size of a unit cell is in the range of 8 to 14 Å, the time needed for the shockwave to pass the unit cell is approximately $2\text{x}10^{-13}$ sec. Hence, the unimolecular rate of the decomposition should be of the order of $5\text{x}10^{12}$ molecules/sec. Considering the Arrhenius relations discussed above, the temperature that corresponds to this rate is roughly 4000K using k_2 and about 2100K using k_3 (see above). The calculated heat capacity of TATP was found to be C_v=173 and 186 cal/(K*mol) at 2000 and 4000K respectively. These decomposition temperatures require reaction exothermicity of 346 and 744 kcal/mol for the 2000 and 4000K respectively. These values should be compared with the calculated exothermicity of the decomposition process. The calculated decomposition exothermicities are far from being sufficient to sustain such high temperatures. As a result we must conclude that the required heat is obtained by converting volume work to heat in the shockwave. The volume work is obtained by the production of approximately four gas phase product molecules from each decomposing solid TATP molecule. A rough estimate of the upper limit for the volume work can be obtained assuming a mole of solid TATP converts to four moles of ideal gas products. The approximate pressure increase, assuming an infinitely rapid conversion that occurs in the volume of one mole of solid TATP, is of the order of 100 bars. The associated energy content is approximately 2500 kcal/mol. This is the origin of the explosive power of solid TATP.

A verification of this hypothesis has been carried out by employing a molecular dynamics simulation (MD). The calculations were carried out

using the ReaxFF reactive force field, extended to reproduce the quantum chemistry (QM)-derived relative energies of the reactants, products, intermediates and transition states related to the TATP unimolecular decomposition (van Duin et al. 2005). The primary reaction products and average initiation temperature obtained experimentally match closely with those observed from a TATP-condensed phase cookoff type simulation, indicating that unimolecular decomposition dominates TATP-condensed phase initiation. Furthermore, the reaction products observed in the cookoff simulations match closely with those predicted from the QM-simulations.

Harmonic frequency calculations were performed for the TATP molecule, on both the PM3 (a semi-empirical method) and DFT/cc-pVDZ levels. This data was used to improve semi-empirical potential surfaces by which anharmonic frequency calculation was performed. The anharmonic corrections were obtained using a Vibrational Self-Consistent Field (VSCF) method. Figure 3 shows one of the signature vibrational modes of TATP.

Figure 3. Calculation of the C-C-O bend mode of TATP corresponding to the frequency at 1178 cm^{-1}:

Figure 4 shows a comparison between Raman spectra of closely related peroxides. The spectroscopic fingerprints are the peroxide O-O stretch and the C-O stretch in the ring.

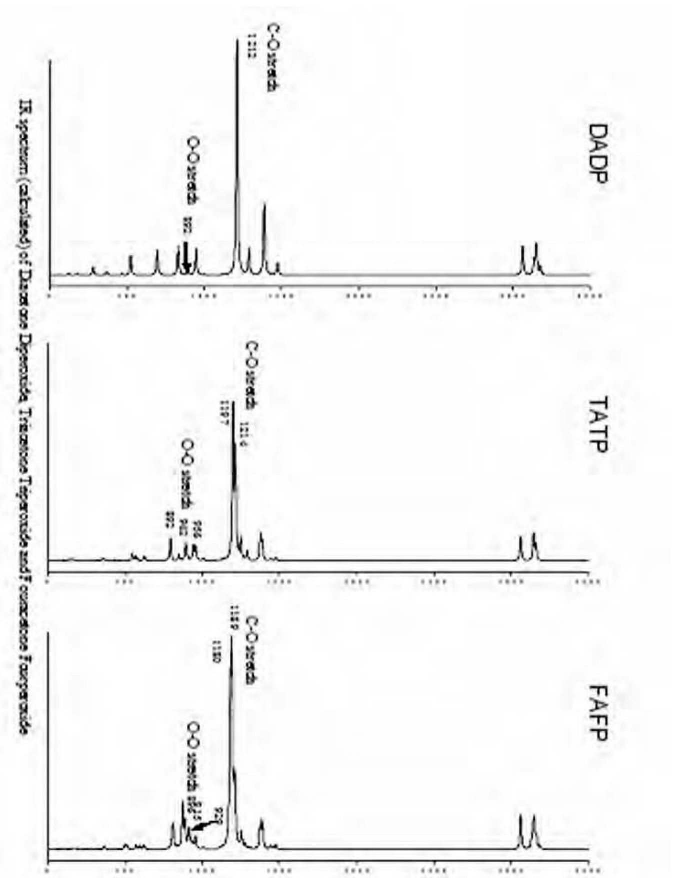

Figure 4. Calculated Raman spectra of explosive peroxides.

3. Conclusions

Electronic structure calculations and molecular dynamics (MD) simulations were employed to study the explosive properties of peroxide based explosives. The applicability of these methods was demonstrated by the excellent agreement between the available experimental data and the calculated ground state structure and vibrational IR and Raman spectra (Dubnikova et. al 2005). The calculated thermal decomposition pathway of the TATP molecule was found to be a complicated multi-step process with several highly reactive intermediates along the decomposition pathway, including singlet molecular oxygen and various biradicals. Acetone, and ozone are predicted to be the main products, along with dioxygen, methyl acetate, ethane and carbon dioxide. These decomposition products were

indeed observed experimentally. The predicted rate-determining step, which has an energy barrier of approximately 34-37 kcal/mol, involves homolytic cleavage of one peroxide bond with concomitant stretching of a neighboring C-O bonds. It is noteworthy that the calculations predict formation of ozone as well as oxygen molecules in the decomposition process and not the intuitively expected oxidation products. The key conclusion from this study is that the explosion of TATP is not a thermochemically highly favored event. It rather involves entropy burst, which is the result of formation of four gas-phase molecules from every TATP molecule in the solid state. Quite unexpectedly, the three isopropylidene units of the TATP molecule do not play the role of fuel that may be oxidized and release energy during the explosion event. Instead, these units function as molecular scaffolds that hold the three peroxide units in close spatial proximity and appropriate orientation for the decomposition chain reaction.

The molecular dynamics (MD) simulations (van Duin et al. 2005) confirm that condensed phase TATP-initiation is entropy-, not enthalpy driven, as the initiation reaction, which mainly leads to the formation of acetone, O_2 and several unstable $C_3H_6O_2$-isomers, is almost energy-neutral. The O_2 generated in the initiation steps is subsequently utilized in exothermic secondary reactions leading to the formation of water and a wide range of small aldehydes, ketones, ethers and alcohols.

The calculations described here which have been mostly confirmed experimentally provide the basis for further work which is aimed to find reliable methods for detection of TATP and its close peroxide derivatives.

Acknowledgement

Partial support for this research was obtained from NATO (SFP 980873).

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PEROXIDE EXPLOSIVES

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Presented by Herr Professor Hiltmar Schubert,
St. Petersburg, August 2005

1. Introduction

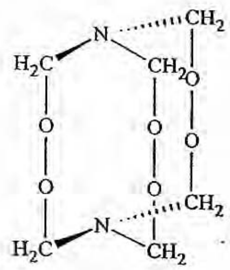
The sensitivity and/or stability of an energetic materials is often assessed by its weakest bond—its trigger linkage (Table 1). This is generally the C-NO_2 in nitrated explosives. In peroxides it is the -O-O- bond.

Table 1. Bond Energies of Weakest Bond.

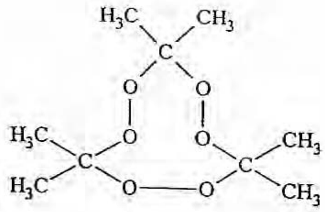
Compound	Trigger Linkage	Bond Energy kJ/mol	Bond Energy kcal/mol	Activation Energy kJ/mol	Activation Energy kcal/mol
nitroarene	C-NO_2	305	73	293	70
nitramine	N-NO_2	163	39	196	47
Nitrate ester	CO-NO_2	222	53	167	40
peroxide	CO-OC	142	34	146	35

There are dozens of peroxide compounds. About ninety percent are used by the polymer industry; the other major usage is beaching and anti-bacterial action. Di-t-butyl and di-benzoyl peroxides are widely used commercially.[1] They are reported to have a TNT equivalency of around 25 to 30%. Peroxides with multiple peroxide functionalities per molecule, such as hexamethylene triperoxide diamine (HMTD) and triacetone triperoxide (TATP), are reported to have much higher TNT equivalencies, on the order of 60 and 88%, respectively.[2,3]

H. Schubert and A. Kuznetsov (eds.), Detection and Disposal of Improvised Explosives, 113–121.



HMTD



TATP

TNT equivalence is not a precise number. It is usually defined by comparing blast overpressure or impulse of the explosive of interest to a similar amount of TNT. Explosive performance can also be compared to TNT by lead block or cylinder expansion or heat of explosion, or best, by detonation velocity. The "value" obtained is highly variable. Nevertheless, the values in Table 2 indicate that TATP and HMTD are only mediocre explosives.

Table 2. Comparative Explosive Performance[2-4].

Explosive	Properties			Detonation	
	mole. wt	melt. pt	density	velocity	% TNT
	g/mol	oC	g/cc	km/s	Trauzl
nitromethane	61	-29	1.1	6.2	110%
PETN	316	143	1.7	8.0	174%
picric acid	229	122	1.8	7.7	105%
Tetryl	287	129	1.7	7.7	144%
TNT	227	81	1.6	6.9	100%
RDX	222	204	1.8	8.6	160%
HMX	296	285d	1.9	9.1	160%
AN	80	169	1.7	3.7*	60%
TATP	222	98	1.2	5.3	88%
HMTD	208	148	1.6	5.1	60%
dibenzoyl peroxide	$C_6H_5(O)COOC(O)C_6H_5$				25%
di-t-butyl peroxide	$(CH_3)_3C\text{-}O\text{-}O\text{-}C(CH_3)_3$				30%
chlorate/vasiline					45%

* estimate

2. Properties

The explosive properties of TATP and HMTD have been known for years, but their high sensitivity made them poor candidates for legitimate military use (Table 3).

Table 3. Explosive History[2].

black powder	nitrocellulose nitroglycerin	picric acid	TNT	PETN	TATP	RDX	HMTD	
220	~1840	1742	1863	1894	1895	1899	1900	discovery
1242	~1860	1870	1900	1930	~1950	1940	~1950	use

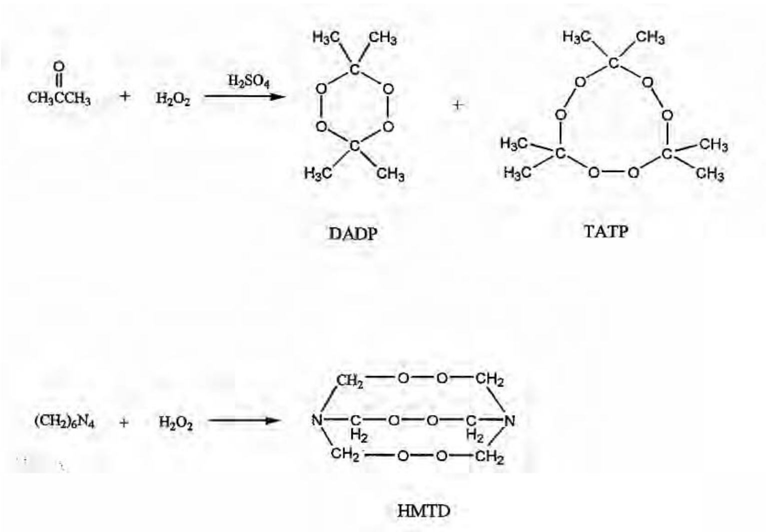
However, their value to terrorists is not their performance. It is the ease with which the materials required for their preparation can be obtained and their high sensitivity, which allows them to function as the explosive initiator. Table 4 was constructed from incidents reported at a meeting held in the Defense Science and Technology Lab (U.K.) in December 2001, just days before Richard Reid attempted to set off a shoe bomb using TATP. Since that time, use of peroxide explosives has escalated from suicide bombers in Israel to those in London.

Table 4. Early Terrorist/Criminal Incidents involving Peroxide Explosives.

Incident	TATP/ HMTD	Year	Location	Size	Juveniles
Israel has experienced the largest bombs					
UX pipe bomb (taught in Soviet Union)	T	1980	Israel	pipe	N
X & UX pipe bomb	T	1982	Israel	1 Kg	N
clandestine lab	T	1998	Israel	100's Kg	N
US had 12 incidents, 9 during bomb prep., 13 injured, 16 recoveries since mid-1980					
UX blasting cap	T	1983	CA	cap	N
blast in prep of pb	T	1989	MD	initiator	4
UX pipe bombs (77)	T/H		CO	initiators	N
powder	T	1990	FL	16 g	N
recovered from car	H	1999	WA	17 g	N
England has had about the same level of use as USA.					
UX devices & ingredients	T	1995	London	2 devices	N
chlorate car bomb	T?	1999	London	initiator	N
ingredients & devices	H	2000	England		1
Australia had 6 incidents all pipe bombs, half with juveniles.					
Others					
Philippine Airline bomb	T?	1994	Manila to Tokyo	initiator?	N
recovered from apartment fire	T	1995	Manila	1 Kg	N
American Airline (shoe bomb 60g PETN)	T	2001	Paris to Miami	initiator (1g)	N

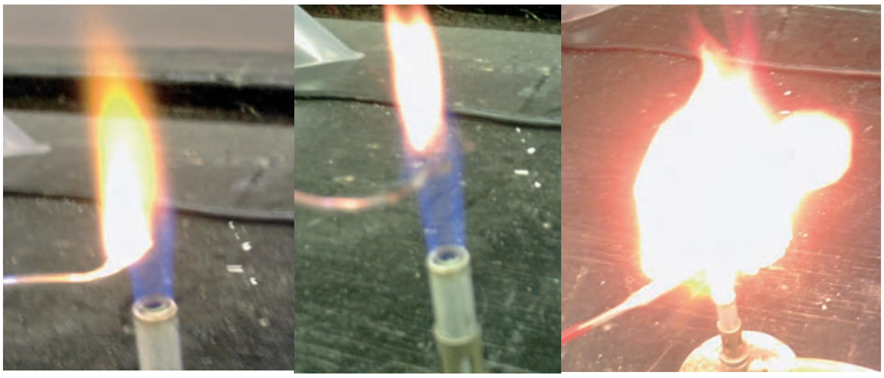
T = TATP; H = HMTD

Recipes for preparing peroxide explosives are on the Internet. Using acid catalyst, hydrogen peroxide and acetone form TATP or hydrogen peroxide and hexamine form HMTD. [5-7]



3. Detection

There are a number of ways to detect peroxides. Chemical tests include treatment of a dilute, acidified permanganate solution with a few crystals of the suspect peroxide. If the suspect crystals are peroxide, the pink permanganate solution turns clear. Test kits are sold specifically for the peroxide explosives. One developed in Israel is the ETK, five tube kit. However, the simplest test of all is the flame test. A bright whoosh of a flame readily distinguishes between white powders--sugar, salt, illegal drugs and explosives. Caution: test less than a match head amount of material.



RDX sugar TATP

TATP is highly volatile (vapor pressure ~ 0.03 mm).[5] This means it readily sublimes. Before law enforcement was aware that its sublimation was so easy, TATP was thought to detonate without leaving any residue. Generally, the post-blast residue of an explosive is only the material spalled from the original explosives. Transformation products are not observed. Peracetic acid has been reportedly found in the detonation products of TATP, but in general, only traces of TATP are found.

TATP is highly volatile; therefore, it is readily detectable--it is easy to get into a vapor detector. One vapor detector is the canine. Because TATP is difficult to handle, we have prepared canine training aids. TATP vapors are allowed to permeate clean cotton balls. Up to 800 mg can be captured per gram cotton. In general, we observed that in a few passes by the training aid, dogs recognized the odor of TATP. The training aid are effective for months if properly sealed. In a test conducted at Global Training Academy in San Antonio, Texas, two dogs trained with the training aids were asked

to search for 0.3 g of solid TATP. They alerted on the training aid and on the solid TATP. In fact, one dog alerted early, we presume because the scent cone for TATP was extremely large. It is important to note that the dogs did not alert on acetone.[8]

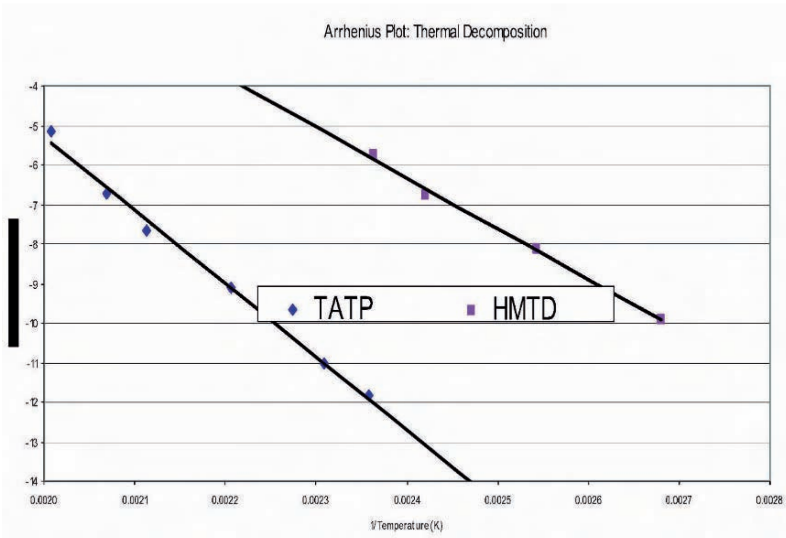
Once dogs find an illegal stash of TATP or HMTD, the question becomes how to safely dispose of it. While "blow-in-place" is a well-accepted practice, it is not always feasible. We are seeking a wet-chemical method of destruction. To that purpose, the solubilities of TATP and HMTD are reported in Table 5.

Table 5[9]. Solubilities in g/100 mL Solvent.

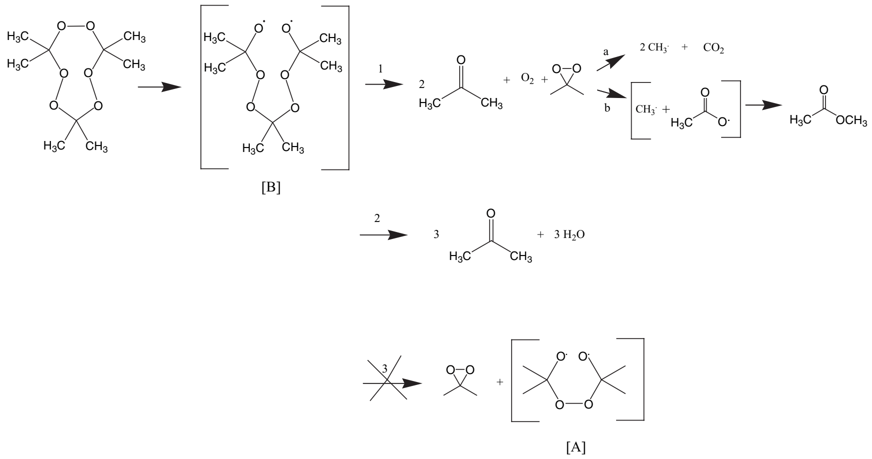
Solvent	TATP	HMTD	AN	TNT	RDX	HMX	PETN
water (cold)	S	0.01	65	0.013	0.005		
water (hot)	S	0.1	150	--	0.03		
caustic solution	S	destroyed		--	--		
acidic solution	dec in w sulfuric	**		--	--		
chloroform	111	0.64		19	--		
toluene	35			55	0.02		
acetone	17	0.33		109	6.8	0.96	25
hexane*	11			0.16	--		
diethyl ether	6	0.02		3.3	--		
ethanol	4	0.01	2.5	1.23	0.24		
i-propanol			3.2				

S= slightly soluble * * HMTD is reported to form RDX with nitric acid.
* Hexanes is representative of other hydrocarbons, I.e. gasoline & diesel

The stability and sensitivity of peroxides are always important issues.[10] In fact, special U.N. Transportation testing protocols have been designed for peroxides. Low-molecular-weight, primary dialkyl peroxides are shock-sensitive and explosive. Their sensitivity decreases with increasing molecular weight. Generally, di-tertiary alkyl peroxides $R_3C\text{-}O\text{-}O\text{-}CR_3$ are more stable than primary or secondary $R_2HC\text{-}O\text{-}O\text{-}CHR_2$. Thus, most commercial peroxides are di-tertiary: di-t-butyl peroxide $(CH_3)_3COOC(CH_3)_3$ and di-cumyl peroxide $(C_6H_5)(CH_3)_2C\text{-}O\text{-}O\text{-}C(CH_3)_2(C_6H_5)$. These are relatively stable, but it should be noted that contamination such as with acid, base, metals, or amines makes peroxides more sensitive.



We have investigated the thermal decomposition of triacetone triperoxide (TATP) over the temperature range 151 to 230°C and found it to be first order out to a high degree of conversion. Arrhenius parameters were calculated--activation energy, 151 kJ/mol (36.3 kcal/mol) and pre-exponential factor, 3.75×10^{13} s^{-1}. Under all conditions the principle decomposition products were acetone (about 2 mole per mole TATP in the gas-phase and 2.5-2.6 mole per mole in condensed-phase) and carbon dioxide. Minor products included some ascribed to reactions of methyl radical: ethane, methanol, 2-butanone, ethyl acetate; these increased at high temperature. Methyl acetate and acetic acid were also formed in the decomposition of neat TATP; the former was more evident in the gas-phase decompositions (151°C and 230°C) and the latter in the condensed-phase decompositions (151°C). The decomposition of TATP in condensed-phase or in hydrogen-donating solvents enhanced acetone production, suppressed CO_2 production, and slightly increased the rate constant (a factor of 2-3). All observations were interpreted in terms of decomposition pathways initiated by O-O homolysis.[6]



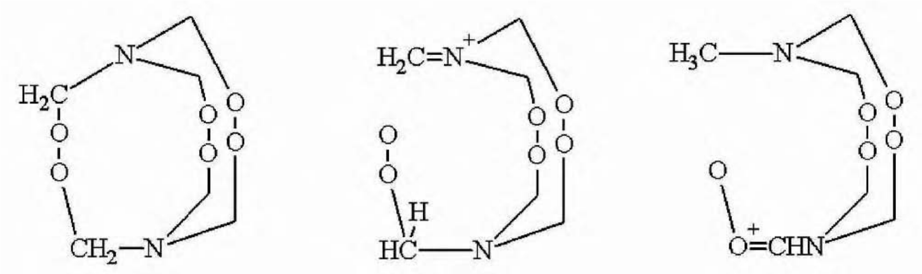
Proposed Decomposition of TATP (1) favored in gas phase (a) high temperature, (b) low temperature; (2) favored in condensed phase or hydrogen-donating solvents

Using a similar protocol to that described for TATP, the thermal decomposition of neat hexamethylene triperoxide diamine (HMTD) was examined over the temperature range 100°C and 180°C. It was found to be first-order up to 150°C and initiated by the elimination of O_2. Subsequent decomposition formed CO_2 (about 2 moles per mole HMTD), trimethylamine, and ammonia. Above 150°C, the decomposition became nearly instantaneous, and the decomposition products changed. Instead of carbon dioxide, CO was the main product (about 3 mole per mole HMTD), and when the thermolysis was performed under air, no trimethylamine was observed. The initiating step for HMTD decomposition is believed to remain the same. The observed changes are interpreted in terms of the addition of a secondary reaction—the oxidation of trimethylamine to HCN and methanol. This interpretation is based on the fact that when available oxygen was limited, i.e. when the decomposition was performed under vacuum, some trimethylamine was observed in the high temperature thermolysis.[7]

at or below 150°C, in air or vacuum: $C_6H_{12}O_6N_2 \leftrightarrow 3\ CO_2 + N(CH_3)_3 + NH_3$

at 160-180°C in vacuum: $C_6H_{12}O_6N_2 \leftrightarrow 3\ CO + N(CH_3)_3 + \frac{1}{2}\ N_2 + 1.5H_2O + \frac{1}{2}\ O_2$

at or above 160°C in air: $N(CH_3)_3 + O_2 \leftrightarrow HCN + 2\ CH_3OH$



Proposed Ionic Decomposition Scheme of HMTD[7]

In summary, the peroxide explosives TATP and HMTD, though more sensitive than most military explosives, are within the norm of stabilities for organic compounds. They are special in the ease with which the ingredients for their preparation can be obtained and in the fact that they can function as primary explosives. TATP has the added unusual property of readily subliming.

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ASSOCIATED PARTICLE IMAGING: AN ENABLING TECHNOLOGY OF DETECTION OF IMPROVISED EXPLOSIVES

DR. GARY W. CARRIVEAU
Director of Api Programs

1. Introduction

Associated Particle Imaging (API) technology provides an important resource to be used in the detection and identification of conventional and/or improvised explosives. Based on the classic "neutron in – gamma out" approach of non-intrusive interrogation, API can be used to find and identify concealed threat materials. The critical difference between API and other neutron interrogation methods is the ability to significantly reduce the impact of "background clutter" in the signal-to-noise ratio caused by the material surrounding and adjacent to the threat.

2. The Associated Particle Technology

The key API technical capabilities are:

- Able to penetrate barriers concealing the threat material, including steel and concrete
- Provides material identification and/or classification of hidden threats
- Provides 3-dimentionsal mapping of the contents of sealed containers
- Small, portable, and low power
- Safe to use in open environments
- Can be used when only one side of the container is available

The API technology follows the neutron in – gamma out approach: a source of neutrons may be used to interrogate hidden material inside of a sealed container. The neutrons interact with the interior material and some of the incident neutrons interact with the atomic nuclei of the hidden material and create gamma rays. The detection of the characteristic gamma rays provides information concerning the amount and type of hidden material detected.

H. Schubert and A. Kuznetsov (eds.), Detection and Disposal of Improvised Explosives, 123–125.

The traditional approach as been used for decades, however, it has some severe limitations. Gamma rays resulting from surrounding clutter, for example, the ground, structural components, items intended to hide the threat, the barrier material, etc., may all be sources of background “noise” in the neutron interrogation. The API method employs one important additional feature added to this general neutron interrogation method. This improvement relies on “tagging” the individual neutrons used in the interrogation so that only those gamma rays that are produced in the region of interest that contains the threat material are counted. The result is a greatly improved signal-to-noise ratio for API compared to other neutron in – gamma out devices.

The API device employs an electronic neutron generator (other neutron in – gamma out devices often use a radioactive source). The neutron tagging is accomplished by detecting the direction and time of arrival of the alpha particle that is associated with the generation of an individual neutron in the neutron generator. This allows one to “use” only those neutrons (and any gamma rays that they may produce) from the region of interest containing the threat material. The influence of gamma rays from background clutter material is significantly reduced; this greatly improves the probability of detection and reduces the incidence of false alarms.

3. Field Experiences

Field trials have been performed using a recently developed API system, used for inspection of hidden materials sealed inside of a shipping container. There were several challenges found in this work, including:

- To image and characterize/identify different materials concealed within a closed standard large steel-walled shipping container
- Addressing the problem of the influence of background clutter
- Quantities of simulated thread materials were only ~ 10 kg
- Disparate materials were placed adjacent and/or on top of each other
- Access available only from one side
- Standoff distance (between neutron source and threat material) of 2 meters (or more)

With interrogation times of the order of 10 minutes the concealed simulates theat materials were able to be graphically depicted in 3-dimensions and the “tagged” neutron interactions enabled the simulated threat test materials to be correctly identified. This was accomplished even though several disparate materials were placed on top of each other.

4. Conclusion

Conclusion, based on this work, include:

- Inspection was possible through the steel wall of the shipping container from one side only
- The API system could successfully discriminate between and characterize different simulated threat and other materials placed very near by
- The analysis could be accomplished at a standoff distance > 2 meters in an inspection time of ~ 15 minutes
- The inspection time could be reduced with further system optimization

Additional field trials were performed using the API system to find and identify landmines and improvised explosive devices. The device is one of only a few technologies that actually confirm the absence or presence of the high explosive charge associated with the mine or IED.

A note on operational safety. API emits only a very low level of radiation. A single API inspection scan at 3 meters distance from the neutron source imparts a radiation dose of 2 mrems. This is less than the absorbed dose associated with a coast to coast flight across the United States. It is only ~1/2% of the average natural background radiation dose per year. It would required exposure to thousands of scans to approach the level of exposure limitations allowed for occupational exposure per year.

This short note describes some of the recent developments of the API device developed by Applied Signal Technology, Inc. Of course, there are many areas of potential improvements and these are currently being addressed. They include:

- Reduced size/weight/power
- Advanced gamma detectors
- Longer life and higher yield sealed tube neutron source
- Improved alpha detector
- Advanced high speed electronics
- Improved analysis algorithms

5. Summery

- API provides unique inspection capabilities
- Important security missions have been identified
- An ongoing development program is underway

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EXPERIENCE OF APPLICATION OF EXPLOSIVES DETECTORS BY FORENSIC SCIENCE UNITS OF THE MINISTRY OF INTERIOR OF RUSSIAN FEDERATION

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At present due to the increasing of terrorist activity all over the world, especially against transport objects and infrastructure, application and creation of new types of reliable explosive's detection systems for inspection of passenger and cargo traffic becomes more and more significant. According to the analysis of international experience such systems should be multistage.

The designers of such devices have to solve quite complicated and to some extent contradictory problems, for example:

- high reliability of detection of explosives and explosive devices along with
- fast acting;
- low percentage of false alarms;
- minimal discomfort and embarrassment for passengers.

Estimations of Russian and foreign specialists show, that application of detecting devices based on only one physical-chemical principle can't guarantee reliable detection of explosives.

It is assumed, that an inspecting system should have at least three stages of monitoring, each of them based on different detecting methods.

It is expedient to use fast acting non-destructive methods on the first stage of inspection, even though they may have low probability of detection of explosives. The time of inspection should not exceed 10 seconds, probability of detection of explosive should not be less than 30%.

After the first stage of inspection, objects that are suspected to contain explosives, pass through the second stage, having the probability of false response about 5%, time of inspection being not more than 20-30 sec.

H. Schubert and A. Kuznetsov (eds.), Detection and Disposal of Improvised Explosives, 127–130.

In case of positive result on the second stage, the inspection should be continued with the help of high-performance equipment, having not more than 1% of false alarms.

Total time of three-stage inspection must not exceed 1-2 minutes.

Concrete techniques should be developed for each specific method and type of device in accordance with existing legal regulations, safety techniques and demands of security services.

Detectors of explosives play considerable role in the solution of these problems, most of them being detectors of explosives' vapors.

At present many companies and enterprises, Russian as well foreign, offer detecting devices of mentioned types, providing demanded performance capacities.

Manufacturers permanently upgrade them in accordance with their experience and modern requirements. Miscellaneous types of detecting devices are available on Russian market i.e., obsolete "Echo-M", "M0-1", various versions of "PDP", "Entry Scan", "EVD-3000" and quite modern detectors "M0-2", "Ion Scan-400", "Itemiser", and "E-3500".

The analysis of application of these means shows, that detectors of explosives' operated by qualified personnel ensure reliable detection of bulk quantities of all widespread explosives and almost all of them in traces.

Detection of traces of explosives is most actual and frequent task while searching the sources of illegal turnover of explosives and camouflaged explosive devices. However, due to the lack of funding law enforcement structures are not sufficiently equipped with such means. New models of detectors now being in development require as a rule high-qualified maintenance and developed service and testing net all over the country.

The existing detectors with sensitivity about 10^{-14} g/cm^3 (TNT) make some particular demands to their operating conditions and qualification of the operators. Further development of such devices, implying the increase of their sensitivity up to 10^{-17} g/cm^3 will toughen demands to the rooms and staff.

Modern approach to the problem is reduction of the price of devices, their mass, dimensions and power consumption without considerable impact on their sensitivity in order to expand the monitoring net and thus to increase probability of detection of explosives and involved persons. In future almost all field officers of law enforcement services are planned to be equipped with portable explosive sensors (detectors).

However all mentioned devices were developed only for detection of quite narrow spectrum of explosives, these explosives as a rule being commercially manufactured and used for industrial or military purposes. Percentage of such explosives in total criminal turnover is permanently

decreasing due to the toughening of control measures for legal turnover of explosives. On the contrary, the number of improvised explosives and explosive devices both seized and used tends to increase. Among them are organic explosive peroxides, which are non-detectable by majority of existing detectors. Therefore creation of explosives' detectors with expanded spectrum of detectable explosives is the task of most actuality.

Due to their performance parameters detectors are expedient to be used mainly by field divisions of law enforcement and security services.

Detectors are not used by explosive technicians of forensic service of Ministry of Interior of Russia in their daily practice, because the tasks of forensic research are much more complicated and miscellaneous, than simple detection of presence of explosive or its traces, i.e. determination of the type (sort, brand) of explosive, some other significant attributes, documentation of the investigation results in accordance with legal requirements – all these tasks demand special analytical equipment.

Increasing of authenticity of explosives' identification is of great importance for forensic investigations in terms of conclusive significance of results of forensic research all over the world. No other method can compete in this field of investigation with mass-spectroscopy. Chromatographs with mass-selective detectors at present are main devices to do this work. Capillary electrophoresis is intensively developed and applied as analytical method. Some Russian companies make attempts to create devices, combining advantages of ion-mobility detectors and MSD of analytical equipment.

Due to the great variety of problems and tasks forensic explosive technicians have to solve, we try to be aware of new research in the field of explosives' detecting and disposal of explosive devices.

Application of explosives' detectors in the field of forensic research is expedient on the stage of preliminary examination of evidence in order to detect traces of explosives. Modern versions of such devices allow determining the presence of explosive inside suspicious objects by detecting traces of explosives on their surface, this being of great importance in terms of safety of investigations.

Application of explosives' detectors for searching traces of explosives on the evidence, especially on the clothes of suspects, is quite useful. Traditional methods of searching of explosives' traces imply making of washouts from the surface of the objects, and as a result micro quantities of explosive are dispersed over the surface.

Application of sensitive detectors makes it possible to determine location of explosive particles and traces and then to make dot washouts from these places. Concentration of required substances in such washouts (extracts) is much higher and level of accompanying pollution – much

lower, which allows one to increase signal/noise ratio. Thus general effectiveness of forensic investigation and conclusive significance of its results increase greatly. Application of detectors also makes it possible to select the most informative objects of evidence brought from the explosion site at the stage of preliminary examination.

Application of detectors in special actions of law enforcement services allows one to detect almost immediately traces of explosives on the suspects' body or other objects, during the searches of apartments, cars etc.

Our analysis of application of explosives' detectors by various security services showed that general effectiveness of security systems deteriorate greatly due to the low level of professional skill and knowledge, lack of professional training, absence of unified methodical support and common single approach to the application of technical means. Similar problems occur in application of traditional means, in particular dogs. Thus expenses for purchase of new equipment can turn out to be senseless.

Therefore we consider profound training of the staff and thorough development of inspection methods for cargo traffic, luggage and passengers themselves to be the most actual tasks.

There is no sense to supply security services with new equipment until these problems are solved. To say more, the existing order of things causes unjustified "calming" of security specialists.

Requirements to detecting devices are determined by the specific character of tasks and problems, which have to be solved by various security services. Forensic scientists of Ministry of Interior are most experienced specialists in the field of detecting of explosives and managing of high-tech equipment. General effectiveness of application of explosives' detectors depends greatly upon interaction and co-operation between different units and services of Ministry of Interior. Our experience in turn can be used for development of legal regulations and instructions for specialists dealing with examination of passengers and cargo traffic.

TECHNICAL MASKING OF IMPROVISED EXPLOSIVE DEVICES

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1. Introduction

Searching for IED systems in buildings, premises, streets etc. is very demanding from the technical point of view and it will never be possible to provide preventive protection anytime and anywhere. Searching for IED on persons and in their baggage is at present generally considered possible and at the same time necessary[1] in case of entrances[2] into important and sensitive objects, e.g. aircraft, important government buildings, nuclear power plants etc. Unless, under the given circumstances, the terrorists are able to attack a properly protected important target, they will choose another target but the less protected one. Nevertheless they will try their best to continue inquiring into the possibilities of attacking the more important and better protected target. The crucial burden of solving the situation consists in the developing teams and firms producing the detection technology. There is a question concerning the reliability of these screenings at present and their prospects. Security managers focus on weak points of the IED detection during the screening of people and luggage. The best way how to discover these weak points is to try to think as a terrorist does.

The weakest point of the screening is usually the servicing staff. Thanks to the progress in the detection technology the proportion of automatization during security screenings is on the increase and the human factor of the security screening is inscrutable for both sides. The potential attacker will certainly be interested in the way of masking his/her IED to mislead not only the security screening staff but also the automatic detection of the explosive by a device. It means first of all how to mask technically the explosive and the detonator. It can be supposed that the potential attacker will know neither the exact parameters of the detection technology, especially its concrete setting (for instance sensitivity) in the certain post of the security screening, nor the specific system of devices. But what must be

[1] Even if the possibilities of financing or in practice the willingness to finance seems worse.
[2] Mostly the weakest point of the security service.

H. Schubert and A. Kuznetsov (eds.), Detection and Disposal of Improvised Explosives, 131–142.

taken into consideration is the fact a number of attackers will be familiar with the physical principles of detection devices as well as with their basic defects/faults.[3]

2. Faults of the Typical Contemporary Systems of Detection Devices

The contemporary security body and carry-on baggage screening systems usually consist of a walk-through arch way metal detector, a hand-held metal detector, an x-ray system for baggage screening, usually with dual energy (from one angle of view), rarely with a back scatter or an effective computer tomography, sometimes of an explosives detector mostly with the manual sampling by vacuuming vapours and wiping surfaces. Recently the arch ways for the detection of explosives traces have come into use. Exceptionally traditional x-ray systems are used for people screening.

Metal detectors detect electrically conductive materials on the principle of induction of vortex currents and ferromagnetic metals on the principle of changes of orientation of magnetic domains. They do not detect non-magnetic or electrically non-conductive objects. They also do not detect cold arms made of plastics and composites, drugs, ceramic shooting guns. They do not detect explosives at all. Despite this fact they pose a certain complication for the IED to be smuggled through. Walk-through metal detectors usually detect electronic part of the ignition system with a battery (it depends on its size and the pre-set sensitivity of the detector). But the electronic part can be built in a harmless common consumer electronic device screened during the x-ray carry-on luggage screening.[4] The detonator can be more probably installed in the direct contact with the explosive. It can be necessary for the attacker to mask the IED. In case the walk-through metal detector is routinely adjusted not to activate the alarm when people carrying small metal objects (e.g. watches or metal buckles), it will hardly detect metal cases of detonators. Bigger metal objects which do not activate alarm in most adjustments of walk-through metal detectors can serve as a battery masking. The size of the battery for the ignition cannot be substantially miniaturized. It can be supposed that the attacker will use a detonator that will need a certain minimum electric pulse for the ignition for the purpose of a safe handling. Such a battery masking may not be detected

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[3]The public is warned about some faults of the contemporary technology during the promotion of the development and the introduction of new technologies. For instance the statement that x-ray systems with computer tomography or MVT detect even a thin sheet of an explosive points at the fact that the current x-ray systems lack this capability.

[4] During the screening reliability test it sometimes happens that the testing checked person has to put the electronic part of IED (a portable consumer electronic device) into the locker at the entrance of the protected area for the security precaution against eavesdropping. Thus the security staff take from the attacker unknowingly the electronic part of IED.

even in the case that the whole device (e.g. a buckle with a hidden battery) will activate the alarm when passing through the walk-through metal detector. It is a frequently repeated notorious mistake of the servicing staff. When the metal object is subsequently detected on the screened person by a hand-held metal detector (in our case a metal buckle) that emitted signals during several times repeated walk-through metal detector screening it can often happen that the screened person is automatically let in. In its vicinity another bigger metal object can be masked. Using the hand-held metal detector metal objects can be localized quite easily but it is difficult to assess their size. The signal power is in this case much more dependent on the variable distance of the detector and the metal object than on the size of the object. And more over the screened people usually have a lot of metal objects on their bodies. After removing the object that activated the alarm the screened person should walk again through the walk-through metal detector because only a negative detection by this detector guarantees that the screened person has no bigger metal object (conductive), for instance a battery. Even if the servicing staff ask the screened person to take off the belt and to walk through the metal detector arch-way once again not always the object (the belt in this case) is x-rayed. At the entrances of some properties the walk-through metal detectors sensitivity is adjusted so high that the persons have to take off even watches etc. But even under these circumstances the probability of the detection of the metal case of the detonator is not 100% sure. Sometimes the walk-through metal detector is set to a very high sensitivity causing a number of false alarms and the servicing staff lose their trust in it. Recently boots metal detectors[5] capable of comparing the signal symmetry emitted from the boots have come into use. They are useful for the detection of smaller weapons hidden in the boots.[6] But they are not reliable for smaller detonators detection. With all detectors it is necessary to take account of the fact that even an efficient and reliable detonator need not have a metal case (see chapter 5) and the wiring cannot be detected (but they must not be connected into a circuit and thus create an induction loop).

The metal detectors themselves are thus only a bit unpleasant obstacle for the carriers to smuggle them through. But on the other hand the walk-through metal detectors make it unconvenient to pass through the IED igniter. One fact is very important, the detectors thwart electromagnetic shielding of the explosive, for instance by an aluminium foil, from the detection by nuclear electric quadrupole resonance. It is not possible to pass through a vacuum-tight container with metal walls. They would be suitable

[5] IDO Security 2000, 6 Sapir Street, New Industrial Area, Rishon Lezion, Israel, www.idos2000.co.il

[6] In case their metal parts are not too small and are not placed symmetrically in both boots.

for this purpose because even special thin materials made of steel have a negligible coefficient of molecules wall diffusion.

At this point it is necessary to make a small digression from the subject of people and baggage screening. Desk top metal detectors for the detection of of IED in letter envelopes are capable enough to detect a suspicious letter. Even most of bigger letters in fact only rarely contain some bigger metal objects. They contain only various paper clips and staples. The signal emitted by them is weak, they do not activate an alarm. On the other hand the alarm is activated by relatively small button batteries. Theoretically only a chemical initiation is also possible, but practically it would not be certain whether the letter will blast in advance or whether it will blast in the hands of the addressee during the opening.[7] *In this case the attacker would lose a number of other possibilities how to trigger the initiator (the exact time selfdestruction, remote control etc.)*

There are also serious faults in security carry-on baggage screening. X-ray machines without automatic detection of materials corresponding to explosives are not sufficient for a reliable explosives detection. A big problem in the evaluation of x-ray images of the screened baggage is the monotonous job done under the stress especially in peak hours. Unless the x-ray machine is equipped with the Threat Image Projection or if test IEDs are not adequately used the screening staff are not appropriately motivated. The training of servicing staff is very important – the workers should have practice not only in evaluating the x-ray images of baggage containing harmless items, but also practical knowledge of x-ray images of IED and weapons and the ways of their technical masking.[8] When purchasing test IED (or only their x-ray images) not only commercial offers, but much wider spectrum of possibilities should be taken into consideration. Back-scatter x-ray detectors help the staff because back scatter is more intensive in explosives than in inorganic materials. But if the attacker does not plant the explosive into the area where mostly inorganic material or nothing should be presupposed, the servicing staff will hardly distinguish an explosive from a harmless organic material[9] . The automatic detection of a suspicious material will, as well as, only draw the attention by a lighter area on the screen. It is similar with simple dual-energy systems.

In fact most x-ray detectors with the automatic explosives detection operating on the dual-energy principle and scanning from one-angle point

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[7] It also concerns the criminal cases in the Czech Republic.

[8] Not only from x-rays systems, but e.g. explosives from trace particles detectors etc.to know what can be used for technicval masking.

[9] Back scatter x-ray detector installed in a van (ZBV from AS&E) is a unique device for screening cars in streets etc. with people inside (from the health point of view, in some countries unfortunately and illogically not from the legal point of view)

of view do not detect a thin sheet of the explosive[10], especially in case it is covered with at least little amount of a metal based material etc. X-ray detectors with CT do not have this shortage,[11] nevertheless the operator has to select at least one cutting plane on the basis of a common x-ray image in such a way it would pass through the explosive.

In case the operator selects more cutting planes the time of the scanning of one piece of baggage gets longer and this method becomes less suitable at the first stage of screening when it is necessary to screen baggage within a given period of time. Moreover these x-ray methods presuppose a relevant density and an average proton number of explosives.

Trace particles detectors can be based on o number of physical principles and their mutual combinations, e.g. electron capture detection (ECD), (dual) gas chromatography (GC), preselection by a semipermeable membrane, various preconcentrations on special surfaces, Ion Mobility Spectroscopy, modern up-to-date biosensors or various methods of effective but rather expensive mass spectrometry. A possible attacker need not pay attention to the individual principles of trace particles detectors and their specific parameters. During the security checking of people and their luggage by sampling by either vacuuming of vapours or wiping trace particles on surfaces detectors do not detect explosives sufficiently insulated by a casing the material of which has a minimum diffusion coefficient for the explosive particles and whose surface is well cleaned. A perfect impenetrability of walls is perfectly safeguarded with the casing produced by the high vacuum technology – typically made of metal or glass. A high vacuum electrical feedthrough is used as the transfer of the electric pulse to the detonator. At the end the surface is cleaned by rinsing the system in the unsaturated solution of an acid (for glass based material only hydrogen fluoride acid is used) and then in pure distilled water. The explosive encased in this way can be detected neither by any trace particles detector nor be sniffed out by any perfectly trained dog. However from the technical point of view it would be very complicated to make such a system that would look like a common thing and would not attract attention of the servicing staff. A metal case cannot be taken into consideration if it is carried on the body because it would trigger the alarm at the walk-through metal detector.

X-ray systems for people screening are based on backscatter principle. The security x-ray systems for people screening by the passed through x-rays are suitable for the customs inspection not for the detection of explosives - the concealment of explosives in body cavities can be hardly

[10] E.g. American Detasheet or Czech P1 SE M

[11] E.g. CTX 9000 Dsi fron InVision Technologies, 7151 Gateway Boulevard, Newark, CA 94560, USA, www.invision-tech.com

expected. At present it is rather a lengthy procedure to scan people by contemporary backscatter x-ray systems, because a person has to be scanned from at least two sides, at best from four sides. The scanners developed on new physical principles of the scanning system usually work on the basis of rotation around the standing person. The main problems of using x-ray systems are legal objections against the irradiation but these objections are not justifiable regarding to very low doses of about 0,05 μS. The public quite irrationally oppose not only the irradiation itself but also the exposing of intimate parts of a body. It is reasonable but at the same time disputable. So a possible attacker need not expect that the explosive hidden under his/her clothing would be scanned. The only demand is to carry only such an amount of an explosive hidden on his/her body that would not attract the attention.

3. Advanced Principles for Detection of Explosives on People

The urgent need to screen objects including explosives hidden under the clothing of people sped up the development of several new principles. Due to the fact that for the time being they are not wide spread it is difficult to assess their operational characteristics on one hand and on the other hand they represent no obstacle to the attackers.

For a long time there has been offered a principle of a passive imaging of electromagnetic waves – thermal radiation of objects, especially a human body, in wavelengths of the range of infrared radiation and radio waves – of about 3 mm. This imaging is also known as "**millivision**".[12] On the contrary to the classical thermal imaging in the range of 2-5 μm and 8-15 μm, waves of millimetres length penetrate well through the clothing and in contrast with longer electromagnetic waves the image resolution is possible to be used to distinguish a bigger bulk of an explosive hidden under the clothing from a human body. These devices are unique because they can be hardly substituted and they are able to image in real time the contraband hidden under the clothing of people in the range within a couple of tens of metres. Protests by the public against health threats are not taken into consideration. Protest can be acceptable only from the point of view of the protection of privacy, but it is also disputable. To mask a bigger package containing an explosive against this passive system detection appears very difficult. However supposing the checked persons do not carry any bigger things under their clothing. Otherwise the servicing staff will hardly be able to distinguish between an explosive and a harmless organic object. In this

[12] The term of the firm Millimetrix, 100 Venture Way, Hadley, MA 01035, www.milivision.com

range of wavelength it is not possible to determine different kinds of materials. For instance even a small detonator inserted in an explosive cannot be detected because of a worse image resolution.

A relatively perfect three-dimensional image of a body of a scanned person and all objects hidden under his/her clothing can be made by arch way scanners based on **active holography imaging**[13] using electromagnetic waves of the length of approximately 1 cm. The servicing staff could easily detect a contraband on 3 D image showing an improper shape of a human body caused by this contraband. A possible masking layer would have to copy shapes of a fatter human body. As well as in the case of back scatter x-ray detectors and passive imaging of millimetre waves the attacker would probably have other available options of masking thanks to the development of the software to suppress private details of a body.

So called **dielectric portal**[14] will function on the principle of the automatic detection of the contraband carried under the clothing of the scanned person. It will be a big advantage preventing from a human-made mistake. This scanner measures dielectric constant of a human body surface by means of the determination of the reflection coefficient of microwave radiation. The unique character of this device consists in the fact that the shape of the object is not important. The decisive criteria for the automatic detection of the object on the skeleton generated on the screen by the computer are the size of the object, the density of the material and its absorption abilities. An attacker would have to use a relatively thick layer of a material with the same dielectric characteristics as a human body to mask a bigger amount of an explosive. The disability to recognize and display a shape means that this technology does not cause inconvenience to the scanned persons. In case neither the kind of material of the suspicious item is identified nor its image is seen by the staff it means a big number of "false alarms" are activated because the archway will identify as suspicious all bigger objects that the scanned person has on him/her. Small items are not detected at all.

In contrast with the above mentioned screening systems detecting only a bigger object under the clothing **nuclear quadrupole resonance** (NQR) would detect the explosive itself. This is a prospective method how to improve persons screening because unlike the baggage screening it would not have to deal with the issue of the penetration through metal materials. At present owing to the metal detectors all bigger metal objects are, during the security screening, referred to the baggage screening. The advantage is

[13] Safe View, Inc., 469 El Camino, Real Suite 110, Santa Clara, CA 95050, www.safe-view.com

[14] Spatial Dynamics, Inc., 1847 Wilma Drive, Clarkston, WA 99403, USA, www.spatialdynamicsinc.com

the automatic explosive detection regardless of its placing, tension of vapour at the given temperature, vacuum sealing etc.[15]

Another prospective method is the use of **terahertz waves**[16] – spectral analysis of terahertz waves reflected from the scanned person. This method would also enable to identify the kind of material hidden under the clothing.

4. The Advanced Technology for Detection of Explosives in Hand-Held Baggage

One part of the improvement of detection of explosives in baggage is the x-ray systems screening the baggage using the method of **dual energy from several angles of view** during one passage of this piece of luggage.[17] These x-ray systems detect even a thin sheet of the explosive in contrast with computer tomography during the uninterrupted movement of the conveyor. At present these devices are introduced in order to screen checked baggage. If we want to screen them as hand baggage it would be necessary to reduce their size. Both these x-ray methods detect an explosive on the basis of density and an effective proton number of the material. On one hand there is a question whether their adjustment for the automatic detection includes a wide density spectrum of all types of IEDs, on the other hand the adjustment of the automatic detection for a wide spectrum of densities can result in a higher number of false alarms. X-ray images of all baggage classified as suspicious at the first stage of the screening are usually in practice subsequently investigated by the operator. In case even he/she is not positive about the harmlessness of the baggage he/she refers the baggage to the screening procedure using other physical methods. In the decision making process the operators consider the following two points of view. At first whether the material of a suspicious density does not have strange shapes and whether it is not in a strange place, for instance a plastic sheet in the filling of the suitcase lid, a lump of plastic in the radio speaker etc. However plastic explosives can have a shape of a harmless object of a similar density. At second the presence of a possible ignition system can be taken into account especially in the checked baggage. But almost in every piece of luggage there is an electrical device. Therefore it is necessary to search for a kind of connection, typically wires, between the object of suspicious density and the electronic device. It is rather a demanding task in

[15] With drugs regardless the change of the typical density and typical average proton number by making a mixture or a solution suitable for transit.
[16] E.G. TeraView Ltd., Platinum Building, St John's Innovation Park, Cowley Road, Cambridge, CB4 0WS, www.teraview.com
[17] For instance so called multiview tomography by PerkinElmer Detection Systems – Automated Systems, 10E Commerce Way, Woburn, Massachussetts 01801, http://instruments.perkinelmer.com

the usual mess of various things in the luggage. Finally it is necessary to start a search whether there is a detonator in the material of a suspicious density or an object which could serve as a detonator. But even in case no detonator is detected it does not mean that there is not any – see chapter 5. For this reason we urgently need methods of the volume detection in the baggage that exactly detect the explosive. These methods consist in **nuclear quadrupole resonance, x-ray diffraction and "neutron in, gamma out" methods.** The prototypes of "neutron in, gamma out" devices of the end of the 80s and the beginning of the 90s detected only the nucleus of nitrogen atoms, which resulted in numerous false alarms. In addition the devices were too big and heavy. At present there are available even the devices detecting simultaneously the nuclei of nitrogen, carbon, oxygen and hydrogen atoms and their mutual numerical ratio. It enables the automatic explosives detection including the identification of their types. That is a necessary part of the combination of systems for security screening of bigger baggage because even thicker metal sheets do not shield the explosive. But also in case one of these methods is used the explosive can be shielded against the detection. On the other hand this shielding can be easily detected for instance by the measuring of the passed through neutron irradiation.

5. Improvised Detonator without a Metal Parts

One of the significant elements enabling the detection of IED is the detonator. As mentioned above its metal shell made from copper or aluminium, in some cases, activates the alarm in metal detectors. The searching for a detonator in the object that could be an explosive is the basic activity of x-ray systems operators. It concerns especially those packages that are supposed to carry an explosive containing the detonator already. It is quite clear to assume a metal shell of the detonator because at the present market there are probably detonators only with a metal shell,[18] especially for the safety reasons during the large-series production. The unreliable ignition is a weakness of a number of bomb attacks at present.[19] An experienced attacker will require a reliable ignition enabling different

[18] A detonator without a metal shell is not a new idea. For instance in Czechoslovakia before WW II there were designs of detonators with a paper-based sheet because of the low-cost production.

A number of paper detonator was also found in a smuggling case by coastguard authority in Taiwan: Hong, T.Z. Tang C.P. Lin K. The Analysis of the Explosives of the Paper Detonator, In: *Advances in Analysis and Detection of Explosives*. Proceedings of the Symposium on Analysis and Detection of Explosives, September 7-10, 1992, Jerusalem, Israel; Kluwer Academic Publishers.

[19] This also concerns criminal cases in the Czech Rebublic.

options of initiation. There is a problem to what extent it is possible, in the limited conditions, to produce an efficient and thoroughly reliable detonator containing no metal parts or only a minimum of them and having no "thick" outer shell, not even a plastic one, which could display a distinctive contrast on the x-ray device. And in addition the detonator should have various

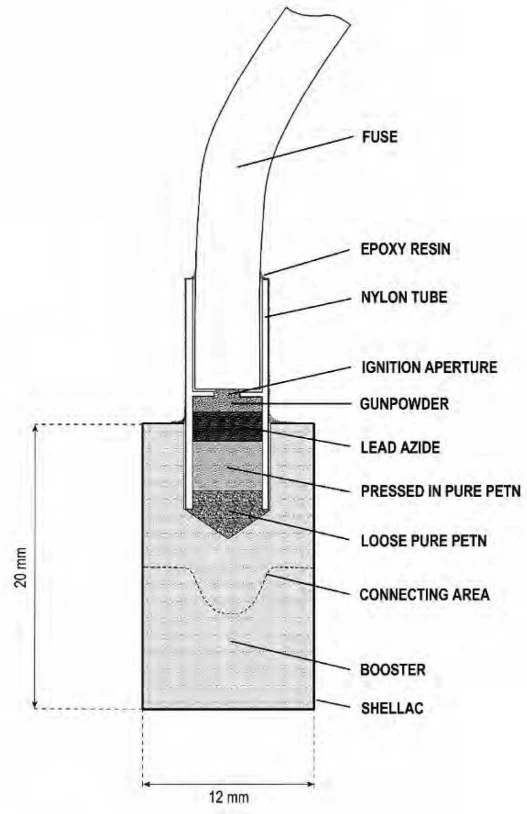

Figure 1. Improvised Detonator.

types of initiation. Its manufacturing was assigned to an experienced expert Mr. Jiří Strnad[20] who managed to manufacture it himself.[21]

The construction of this detonator does not practically differ from the construction of a common detonator. The basic difference consists in the

[20] Dipl. Ing.Jiří Strnad, Ph.D. expert at explosives and primers of the firm Sellier & Bellot, now a visiting lecturer at the department of theory and technology of explosives at the University of Pardubice, www.upce.cz.
[21] Only a metal pressing mould and silon tubes of the initiation element were turned out by a turner.

absence of bigger metal parts. The outer and the biggest part of the detonator is the booster. It is a moulding of pentrit phlegmatized with wax which reinforces the moulding. The moulding is roller-shaped. At one end of the roller there is a cavity for the tube of the initiation element (see the picture). To achieve a higher compression (for a higher detonation velocity) the part was pressed twice. Between the first and the second layer there is a flexure for a better connection. After the pressing the whole part was immersed in the shellac diluted with pure alcohol. The varnish layer protects the shell against wear.

The initiation part is inserted into the booster. The basis of the initiation part is a tube turned of a kind of nylon. The tube is divided into two parts by a partition involving an ignition opening with a diameter of 2 mm. On one side the ignition line is attached. Depending on the type it can be either an electric fusehead with two leading wires or a fuse or a shock tube. On the other side there is the first ignition layer of black powder, then a layer of the explosive – Lead Azide (LA) and pure pentrit is pressed onto this LA layer.

The booster cavity is sprinkled with pure pentrit and the initiation tube is pressed into the booster and the closest area is sealed with resin. This sheetless detonator initiates all kinds of industrial explosives agents. The initiation of improvised explosives is not clearly proved, it would have to be tested. In the negative case it would be no problem to add another booster, a bigger one.

Some x-ray images of the shell-less detonator inserted into less than 1 kilogram of the Semtex 10 explosive were taken by a new type of x-ray system with dual energy. To be more precise an inert version was used. The inert made to order by Mr. Jiří Štancl[22] is identical with the original as to the density and the average proton number (also as to the presence of pentrit, colour and plasticity). As it has been seen in the basic mode of an x-ray image and in the other screening modes the detonator body from the compressed pentrit blends with the Semtex. For a comparison an inert version of the shell-less detonator turned out of PVC[23] was inserted into Semtex 10 too. The material of this inert version is quite clear in the x-ray image.

There are a lot of possibilities of ignition. The one mentioned above was the example of the design of the detonator that need not be shielded with the material of a higher density posing as an unharmful object, because the detonator itself blends with its background – an explosive.

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[22] Dipl.Ing.,Dr. Jiří Štancl, chief of explosives research in the Research Institute of Explosia,a.s., www.explosia.cz

[23] The inert version was manufactured only as a specimen. It is resistant to wear, impacts etc. The real version – the pressing from an explosive – is not so solid, the edges can be cut etc.

6. Conclusion

In conclusion it is necessary to highlight the well-known fact that no physical method is not and will not be sufficient for the security screening if it is used alone - each of them has faults of its own. We must take into consideration that the attackers can use various technical methods of masking IED protecting it from the detection. But it is not possible to mask an IED from more physical principles at a time. To mask an IED from one method can increase the probability to detect it by another method. The terrorists will find it extremely difficult to overcome the barrier created by the combination of more highly automated and mutually cooperating physical principles. There can be an objection that the terrorist will probably focus their attention on less protected targets. But this is the issue of other forms of fight. We cannot admit so big consequences caused by so small force as it can happen in the aviation as well as in other important targets.

RESEARCH AND DEVELOPMENT ON HUMANITARIAN LANDMINE DETECTION SYSTEM BY A COMPACT DISCHARGE-TYPE D-D FUSION NEUTRON SOURCE

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Abstract. Current results are described on the R&D of an anti-personnel landmine detection system by using a discharge-type fusion neutron source. Landmines are to be identified through neutron-captured γ-rays of specific energies by hydrogen and nitrogen atoms in the explosives. Improvements in the neutron source have been made to achieve a dc neutron production rate of 4×10^6 sec^{-1} by a compact device of 200 mm diameter. Also a BGO/NaI(TI) combined scintillation detector has been developed for a well collimated γ-ray detection with an enhanced signal to noise ratio. The results by using an imitator suggest promising and practical features for landmine detection.

Keywords: D-D fusion neutron source; inertial-electrostatic confinement fusion; explosives detection; neutron capture reaction; γ-ray detector

1. Introduction

Described are research and development on an advanced anti-personnel landmine detection system by using a compact discharge-type fusion

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H. Schubert and A. Kuznetsov (eds.), Detection and Disposal of Improvised Explosives, 143–152.

neutron source called IECF (Inertial-Electrostatic Confinement Fusion) [1, 2]. As is schematically shown in Fig. 1, the present detection system makes use of nuclear reactions between the neutrons produced by the IECF source and explosive materials as one of the viable and advanced detection methods, effective to all-plastic mines, in particular, by detecting neutron captured γ-rays of specific energies by hydrogen and nitrogen atoms to identify landmine explosives, as well as backscattered neutrons to find hydrogen anomaly.

The IECF neutron source consists basically of a spherical gridded cathode at the center of a spherical vacuum chamber (serves as an anode) filled with a D_2 fuel gas. A glow discharge takes place between them, thereby, produced ions accelerated toward the center through the gridded cathode undergo D-D fusion reactions through beam-beam or beam-background gas collisions. Thus it utilizes beam-gas colliding fusion, and therefore its long lifetime and long-term dc operation capability are the most advantageous features against conventional beam-target-type fusion neutron sources. The IECF neutron source also has advantages of robustness and easy operation owing to its extremely simple configuration, all of which are essential for the practical landmine detection application.

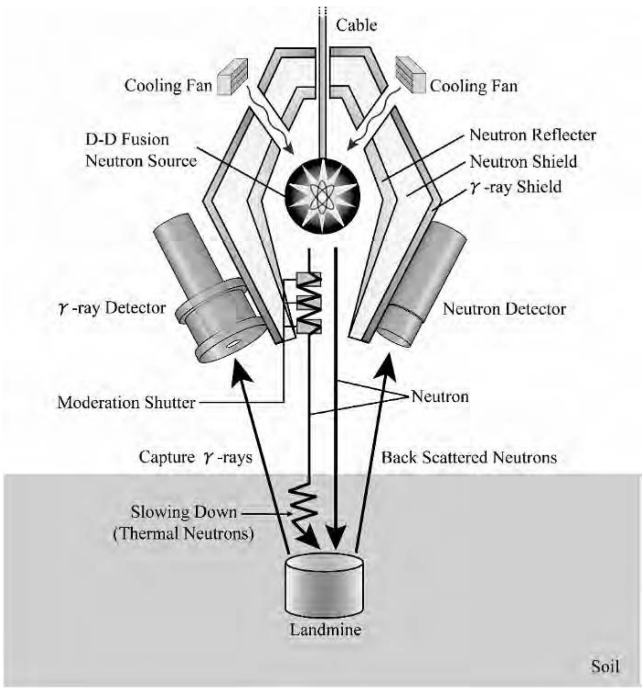


Figure 1. Schematic view of landmine detection method by using an IECF neutron source.

We have developed an extremely compact IECF device of 200 mm in diameter with a titanium getter pump as the main exhaust pump to endure the vibration when it is installed at automobile. Also, analyses and prototype testing have been carried out on envisaged detection system with a newly developed BGO/NaI-combined scintillation detector.

2. Compact Plasma Fusion Neutron Source Developement

An IECF is an extremely compact and simple configuration device as is shown schematically in Fig. 2. The IECF runs by electrical discharge in D-D/D-T/D-^{3}He fuel gases. It basically consists of a hollow cathode at the center of a spherical vacuum chamber (serves as anode) filled with a fuel gas. A glow discharge takes place between them. Ions produced are accelerated toward the cathode, and most of them penetrating the hollow cathode wire and undergo fusion reactions through beam-gas or beam-beam collisions.

By an IECF device of 340 mm diameter in this very simple scheme, we have achieved a dc neutron production rate (NPR) of 1.1×10^7 sec^{-1} (–62 kV, 30 mA) from D-D reactions, and by a larger IECF device with a higher dc voltage applied to the central girded cathode at University of Wisconsin they have achieved a high NPR of 1.8×10^8 sec^{-1} (–180 kV, 67 mA) from D-D reactions [3].

In order to make landmine detection very effective in a shorter time, it is essential to enhance the NPR as high as possible. At the same time, considering the severe environment in practical landmine detection application, robustness and compactness of the equipment are mandatory.

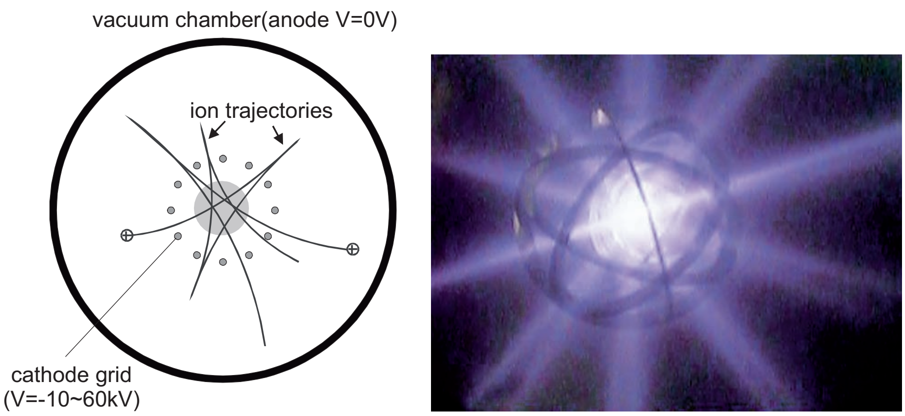


Figure 2. An IECF configuration with a gridded hollow cathode, and a discharge snapshot.

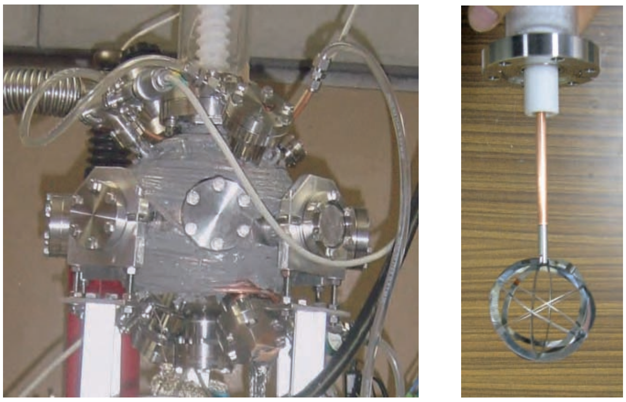


Figure 3. An IECF neutron source. A spherical gridded hollow cathode in the right photo is installed in a spherical vacuum chamber of 200 mm diameter.

In these viewpoints, we have newly developed an extremely compact IECF neutron source of 200 mm diameter (see Fig. 3). In this context, vacuum exhaust is made by a simple titanium getter pump as a main exhaust pump as well as deuterium gas feeder. Currently, the non-evaporation type getter material CapaciTorr B200 (SAES Getter Co.) was found to work very successfully.

The achieved NPR divided by the discharge current is shown in Fig. 4 as a function of the negative high voltage applied to the central gridded cathode. The discharge current ranges from 1 to 55 mA. One can see that the normalized NPR is independent of the discharge current, i.e. NPR is almost proportional to the discharge current. In contrast the NPR depends strongly on the applied voltage to the central cathode grid.

The currently achieved highest NPR in a stable dc operation is 2.2×10^{6} sec^{-1} with –70 kV and 30 mA. A higher voltage up to –100 kV has successfully achieved by a recent upgrade of the high voltage feedthrough system and shows a high normalized NPR of more than 10^{8} sec^{-1} A^{-1} as shown in Fig. 4. The highest NPR observed is 4.4×10^{6} sec^{-1} at –100 kV, 50 mA, though, for a long-term stable operation, the discharge current is limited by a heat removal problem from the outer spherical vacuum chamber. For a more efficient cooling of the chamber, an upgrade device with a full water jacket shown in Fig. 5 has been developed very recently, and is expected to result in an NPR over 10^{7} sec^{-1} in the very near future with –100 kV, 100 mA.

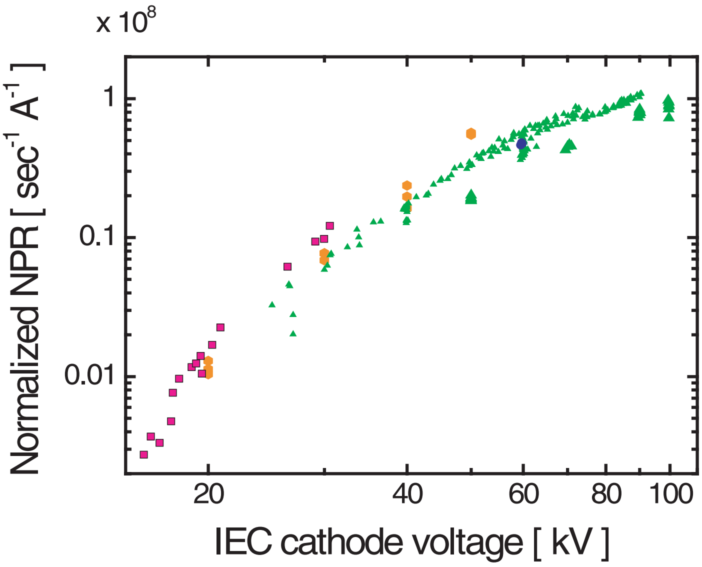


Figure 4. Neutron production rate per discharge current as a function of applied voltage to the central cathode grid. The discharge current ranges from 1 to 80 mA.

Figure 5. An upgraded IECF neutron source with a full water cooling jacket.

3. Development of Detection System for Neutron-Captured γ-Rays

Detection of landmines is carried out by measuring both neutrons and γ-rays from underground when the fusion neutron source irradiates (see Fig. 1). Neutrons emitted from the source are scattered by hydrogen contained in the explosive and then detected by neutron detectors. Also γ-rays of 2.22 MeV and 10.83 MeV are created by capture reactions of thermal neutrons with hydrogen and nitrogen in the explosive, respectively. Since the atomic number ratio in an explosive has a specific value, the type of explosive can be identified by measuring energy spectrum of the γ-rays. A ^{3}He counter

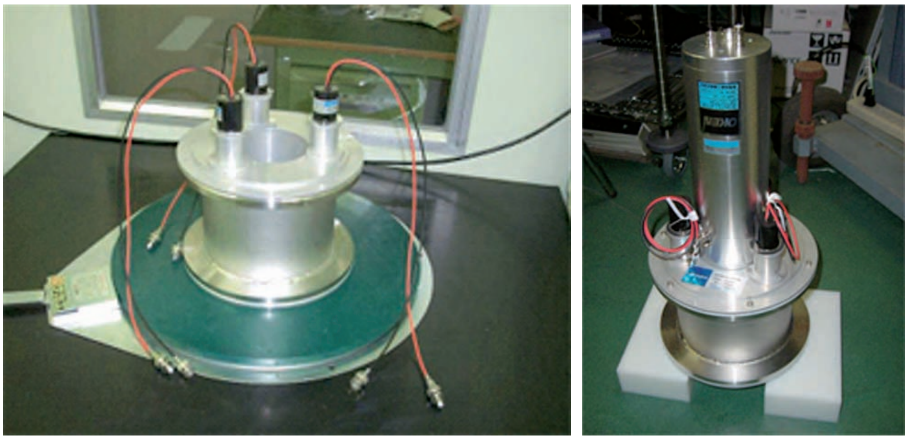


Figure 6. A BGO/NaI(TI) combined scintillator for well collimated γ-ray detection.

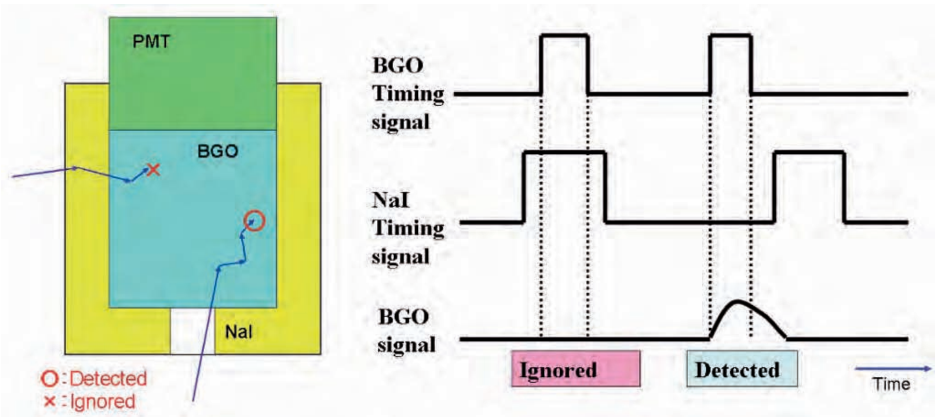


Figure 7. Schematics of anti-coincidence method by the BGO/NaI(TI) combined scintillator.

and organic scintillator (NE-213) are candidates for a neutron detector, and NaI, CsI and BGO scintillators for γ-ray detectors.

As of the γ-ray detector, both for collimation of the γ-ray detection within a specific solid angle and for enhancement of signal to noise ratio, we have developed a BGO/NaI(TI) combined scintillator shown in Fig. 6.

As is schematically shown in Fig. 7, the cylindrical BGO scintillator is placed in the center hole of the annular-shaped NaI(TI) scintillator. γ-rays injected into the BGO scintillator through surrounding NaI(TI) scintillator are rejected through anti-coincidence scheme, while those through the center hole of annular NaI(TI) scintillator are measured. The detection is

thus collimated, and background level of γ-rays can be decreased. Testing results by use of either ^{252}Cf neutron source have shown promising features of the newly developed detector, which are described in detail in [4].

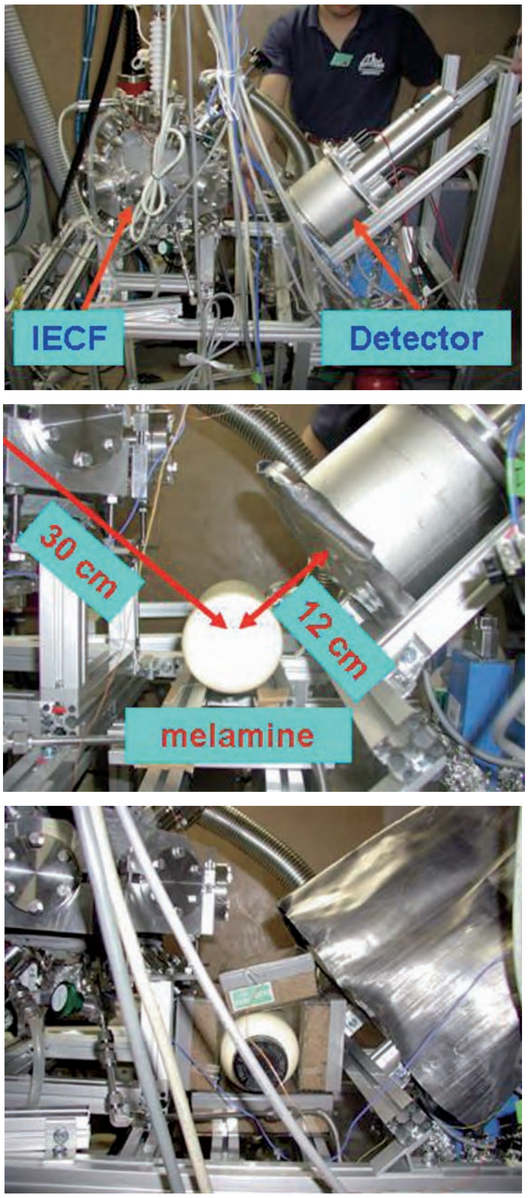
4. Preliminary Detection Testing of Nitrogen in Landmine Imitator

By use of the developed IECF neutron source and the BGO/NaI(TI) combined scintillation detector, laboratory experiments were carried out to identify nitrogen atoms in melamine as a landmine imitator.

Figure 8 shows the experimental layout of the neutron source, scintillation detector, and melamine in a cylindrical cage. As seen in Fig. 8(b), the distances from melamine cage center to the neutron source center, and to the collimation hole in the NaI(TI) scintillator was 30 cm and 12 cm, respectively. As seen in Fig. 8(c), either 4 cm thick boxes of containing sand or 5 cm thick polyethylene blocks were set around the melamine cage as neutron moderator in order to simulate the practical detection of landmines under the ground. One can also see in Fig. 8(c) the detector shielded from X-rays produced by the neutron source by 1 mm thick lead sheet in order for suppressing background noise level.

Figure 9 shows measured γ-ray spectra in this layout with and without 800 g amount of melamine. A clear enhancement is seen in the γ-ray count around 10.83 MeV originating from capture reactions of thermal neutrons with nitrogen in the melamine.

Integrated counts in the region of interest around 10.83 MeV are summarized in the Table 1 for the cases with 800, 270, 60 g amounts of melamine surrounded by polyethylene or soil moderator. The neutron production rate by the IECF source and the counting time duration was 2.2×10^{6} sec^{-1} and 1,500 sec, respectively. It is found that, even with 60 g amount of melamine, the count enhancement is far beyond statistical error. Also, the count enhancement is seen not proportional to the total amount of the melamine, which strongly implies that the count enhancement may be rather proportional to the melamine amount within a specific solid angle of the envisaged collimated detection. The reason for the less enhancement for the cases with the soil than the polyethylene blocks is possibly less thermal neutrons due to the too high neutron energy of 2.45 MeV by the D-D IECF source for the soil thickness of 4 cm. This implies that the present identification system might be applicable to landmines further deep under



(a) (b) (c)

Figure 8. Layout of the neutron source, detector and landmine.

the ground. Also, depending on the depth of interest, the use of moderator shutter schematically shown in Fig. 1 would be effective in order to maximize the signal to noise ratio.

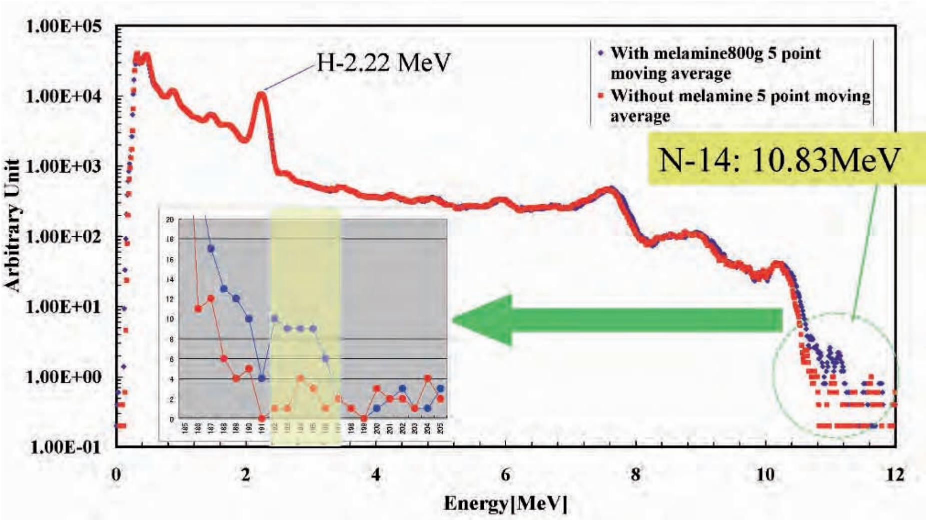


Figure 9. γ-ray spectra with and without 800 g amount of melamine.

Table 1. Integrated γ-ray counts in the region of interest around 10.83 MeV with a neutron production rate of 2.2×10^{6} sec^{-1} and a counting time duration of 1,500 sec.

	5 cm thick polyethylene			4 cm thick soil
amount of melamine	800	270	60	800
count with melamine	102	57	50	61
count w/o melamine	36	38	38	37

5. Conclusion

The developed compact D-D fusion neutron source has shown stable dc neutron production rate of up to 2.2×10^{6} sec^{-1} so far. The developed BGO/NaI(TI) combined scintillator successfully enabled detection of 10.83 MeV γ-rays produced in a landmine imitator containing 60 g melamine. In order to minimize the detection time for practical application to landmine identification, an upgraded IECF neutron source has been developed and will be tested shortly. We expect an enhanced neutron production rate of more than 10^{7} sec^{-1}. We are planning to mount all the equipments onto a remote-controlled vehicle for a field testing scheduled next year.

Acknowledgement

This work has been supported by JST (Japan Science and Technology Agency).

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DETECTION OF NITROAROMATIC DERIVATIVES BY USING REACTIVE ORGANIC THIN LAYERS

Pierre CHARRUE
Lionel HAIRAULT
Didier MATHIEU

NATO Expert Advanced Research Workshop – S[T] PETERSBURG (Russia) 6-11 Sept. 2005

H. Schubert and A. Kuznetsov (eds.), Detection and Disposal of Improvised Explosives, 153–190.

WHY STUDY THE EXPLOSIVES DETECTION ?

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Security (public areas…), Antiterrorism fight, Mines disposal

Counter Proliferation

INTRODUCTION

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- TNT still remains to date the most commonly used explosive in conventionnal ammunitions and, as additive, in civilian explosives
- This material is then available to realize homemade explosive devices for terrorist attacks
- This kind of explosives are generally used in compositions which are wraped up and sealed with paper or plastic film.

Many detection techniques have been investigated up to now in order to improve the sensitivity of the various methods studied in the hardest operating conditions:

-**ultra traces of explosives molecules in vapor phase,**
-**stand off detection (terahertz , nuclear rays technologies, …)**
-**particules detection,**
- **…**

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CHEMICAL SENSORS STUDIES : Explosives detection

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VAPOR PRESSURE IS VERY LOW:

Target to detect	Vapor pressure in ppt à 25 °C (versus sources)
RDX	1 à 6
Pentrit	20 à 200
TNT	1000 à 8000
Nitrobenzene	300 000 000
Ethanol	79 000 000 000

Dionne B. C. et al., *J. Energetic Materials*, 4, 447-472, (1986) et US Environnemental Protection Agency

Some explosives contain specific additives (DMNB, DNT, MNT,EGDN,...) with higher vapor pressure to be detected

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VAPOR PRESSURE OF HIGH EXPLOSIVES

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Litt. source	TNT (ppb)	TNB (ppb)	2,4 DNT (ppb)	HMX (ppt)	RDX (ppt)	Pentrit (ppt)	Tetryl (ppt)	TATP (ppb)	NG (ppb)
US Environnemental Protection Agency (former NOP OU-1)	1,3 (20°C)	289 (25°)	286 (25°C)	-	1,3 (25°C)	-	-		-
US Army Corps of Engineers, Guide for characterization of sits contaminated with energetic materials, Février 2002 (20 °C)	1,4	289	289 (25°C)	4,3	5,5	-	7,5		-
Dionne B. C. et al., J. energetic Materials, 4, 447-472, (1986)	7,7 (25°C)	-	-	-	6 (25°C)	18 (25°C)	-		409 (26°C)
Commercial System for the detecion of explosives, Ecole polytechnique fédérale de Lausanne, (2000)	7.7	-	-	3.95	6	18	-		410
J.C.OXLEY and Al.,Proc of SPIE, The Int. Soc. Of Optical Engineering (2004), 5403 (Pt1,Sensors and ccommand, control communication and intelligence (C3I),Tech. for Homeland Defense III), 246-255	5 (26°C)							46 000 (26°C)	

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MAIN AVAILABLE (TRANS)PORTABLE DETECTION SYSTEMS

System / supplier	Photo	Principle	Cost	Explosives detected	% falses alarms / Response time	weight (kg)	Example of use	Email address
EVD 3000 Scintrex Control screening		Electro chemistry	20,7 k€	RDX, PETN, TNT, SEMTEX, NG, C4, Dynamite, EGDN, DMNB	< 1 minute	3	Israel, Euro 2004, in test in CEA Le Ripault	www.syntrextrace.com
EVD 3500 Scintrex Control screening		Luminescence Chemistry (luminol)	22 k€	RDX, PETN, TNT, NG, NA, EGDN, DMNB, TATP, HMTD, Plastic	1 minute	3	Police, airports	www.syntrextrace.com
IMS IONSCAN 400 B Smiths detection		IMS	20 k€	RDX, HMX PETN, TNT, SEMTEX, NG		22	Aéroport de Paris	
VAPOR TRACER Ion Track		IMS	27 k€	RDX, HMX PETN, TNT, SEMTEX, NA, C4, Dynamite	< 1%	3,2		www.iontrack.com
EGIS DEFENDER Thermo		GC/MS	?	RDX, PETN, NG, EGDN, TATP, HMTD	< 0,2 % - 20 s	25 kg		www.thermo.com

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MAIN AVAILABLE (TRANS)PORTABLE DETECTION SYSTEMS

Système Fournisseur	Photo	Principle	Cost	Explosives detected	% falses alarms / Respon se time	weig ht (kg)	Exemple of use	Email address
SABRE 4000 Smiths detection		IMS	~20 k€	RDX, PETN, TNT, NG, NA, EGDN,	20 s	3,2 kg		
QSH 100 Implant Sc. Corporation		IMS	~20 k€	RDX, PETN, TNT, SEMTEX, NG, C4, Dynamite, EGDN, TATP	< 1% - 10s	6	US Navy	www.implantscience s.com
HOUND Sandia Nat. Gov.		IMS	~45 k€					*Prototypes at the end of development*
µHOUND Sandia Nat. Gov.		IMS/µGC/ SAW	~13 k€					*Prototypes at the end of development*
BIOPROTEC T Nanodetex (Sandia)		µGC/SAW	14,5 k€	Non define To date				Prototype development in progress www.nanodetex.co m
MM2 Brüker		Mass Spectrom etry	200 k€	All organic molecules	15 minutes	37	In use in the french army	www.bruker.fr

INTEREST OF THE THIN LAYERS CHEMICAL SENSORS

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The technologies available to date to detect the explosives are yet expensive, relatively complicated to use and difficult to be used in continuous way

Then, as a complementary technique, it is wished today to propose continuous functionning, cheap and small sized explosive sensors with low cost of production

Thin layers chemical sensors are good candidates for this gap on the market

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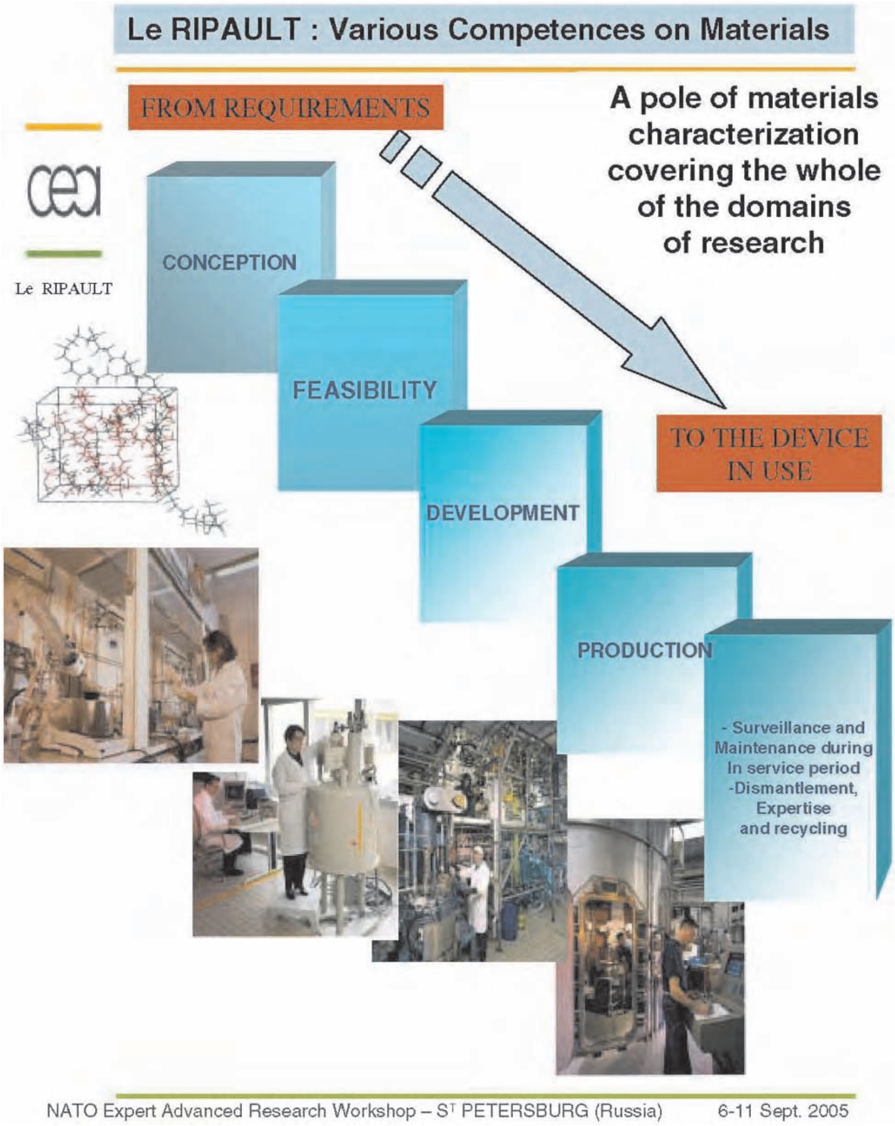
Le RIPAULT : Various Competences on Materials
FROM REQUIREMENTS
A pole of materials characterization covering the whole of the domains of research
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CONCEPTION
FEASIBILITY
DEVELOPMENT
TO THE DEVICE IN USE
PRODUCTION
- Surveillance and Maintenance during In service period
-Dismantlement, Expertise and recycling
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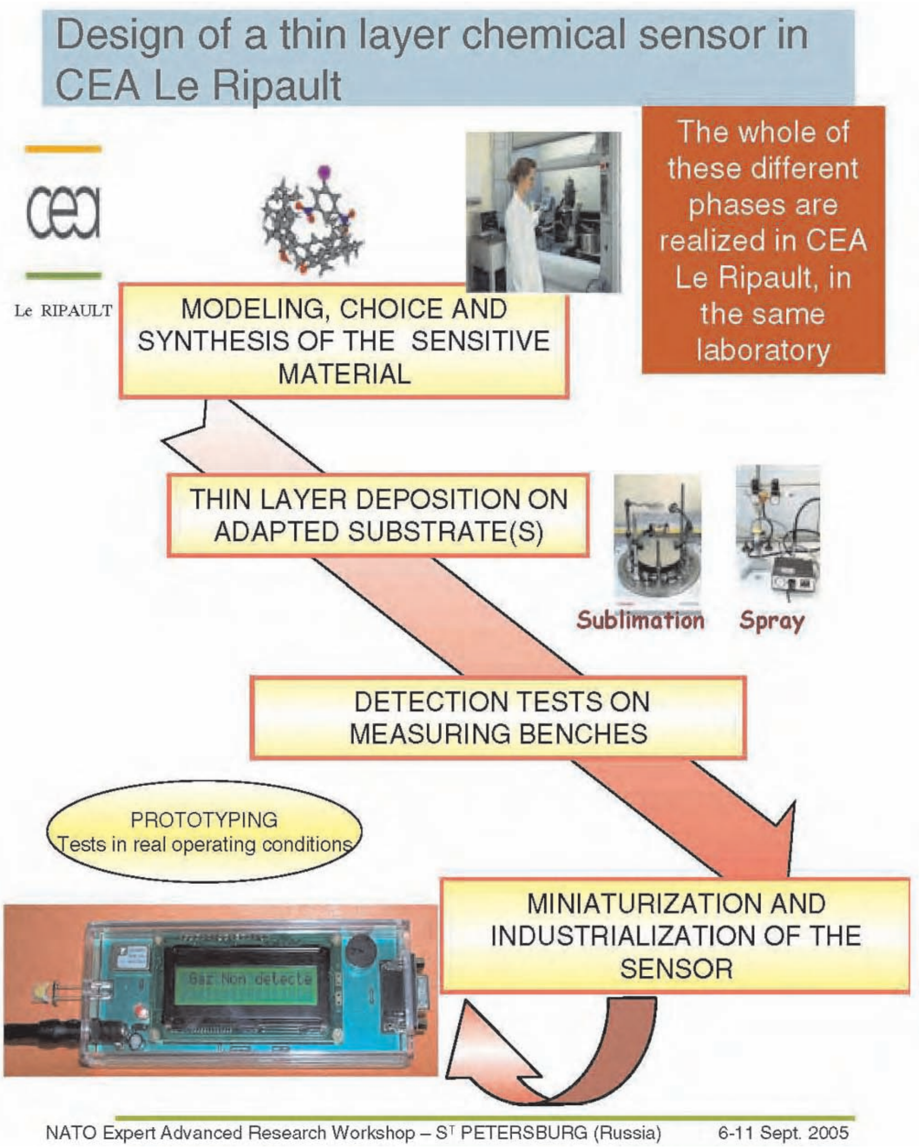
Design of a thin layer chemical sensor in CEA Le Ripault
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The whole of these different phases are realized in CEA Le Ripault, in the same laboratory
MODELING, CHOICE AND SYNTHESIS OF THE SENSITIVE MATERIAL
THIN LAYER DEPOSITION ON ADAPTED SUBSTRATE(S)
Sublimation
Spray
DETECTION TESTS ON MEASURING BENCHES
PROTOTYPING
Tests in real operating conditions
MINIATURIZATION AND INDUSTRIALIZATION OF THE SENSOR
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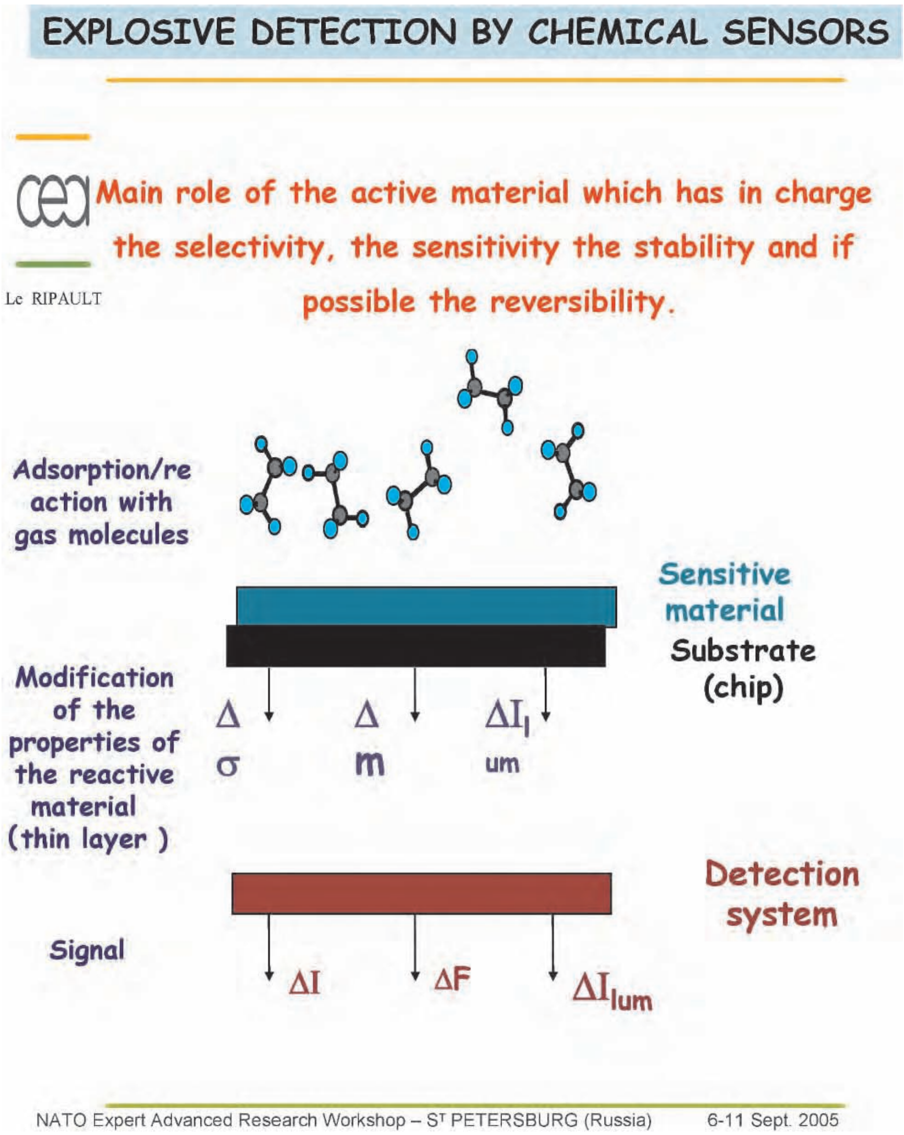
EXPLOSIVE DETECTION BY CHEMICAL SENSORS
Main role of the active material which has in charge the selectivity, the sensitivity the stability and if possible the reversibility.
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Adsorption/reaction with gas molecules
Sensitive material
Substrate (chip)
Modification of the properties of the reactive material (thin layer)
Δσ
Δm
ΔI lum
Detection system
Signal
ΔI
ΔF
ΔI lum
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MOLECULAR MODELING: design of sensitive materials

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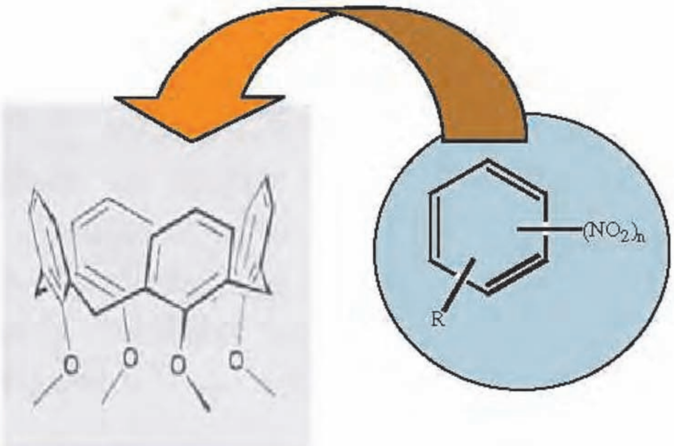
Objective :

- Calculation of the energies of interactions between the supposed sensitive material and the molecules in gas phase to detect.
- Comparison of the results with experimental detection tests using the quartz microbalance device

Choice of a family of sensitive materials:

Calixarenes: influence of the size of the cup (number of patterns of the calixarene) on the efficiency to detect nitroaromatics compounds



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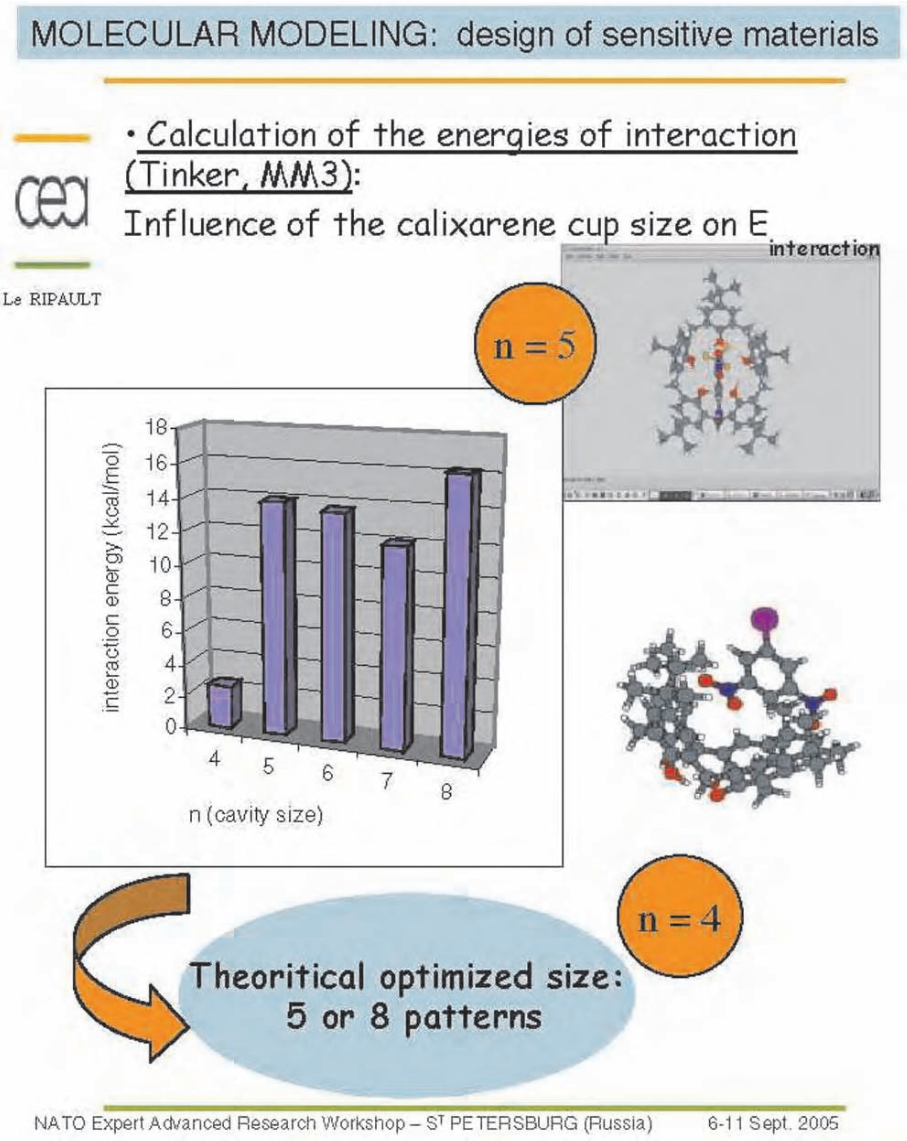
MOLECULAR MODELING: design of sensitive materials
• Calculation of the energies of interaction (Tinker, MM3):
Influence of the calixarene cup size on E interaction
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n = 5
interaction energy (kcal/mol)
18
16
14
12
10
8
6
4
2
0
4
5
6
7
8
n (cavity size)
n = 4
Theoritical optimized size:
5 or 8 patterns
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MOLECULAR MODELING: design of sensitive materials

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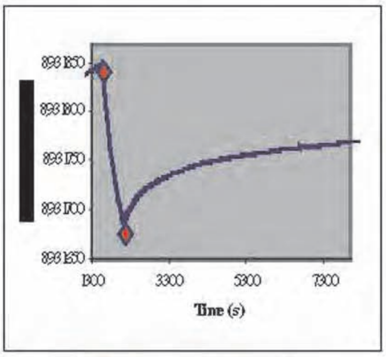
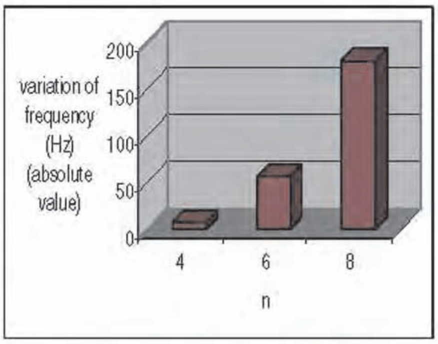
- <u>Detection tests with Quartz Cristal Microbalance substrate (9MHz):</u>
- Experimental Parameters :

Calix[4, 6, 8]arene, quantity deposited # 10 kHz, exposition during 10 minutes to 3 ppm concentration of NA gas.



Detection of 3 ppm of nitroaromatic with the calix[8]arene



Results for the 3 kind of calixarenes

In this configuration, the calix[8]arene is the most efficient pattern in good agreement with the modeling results and then validate this theoritical approach

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QUARTZ CRISTAL MICROBALANCE EXPERIMENTS AT THE LAB SCALE

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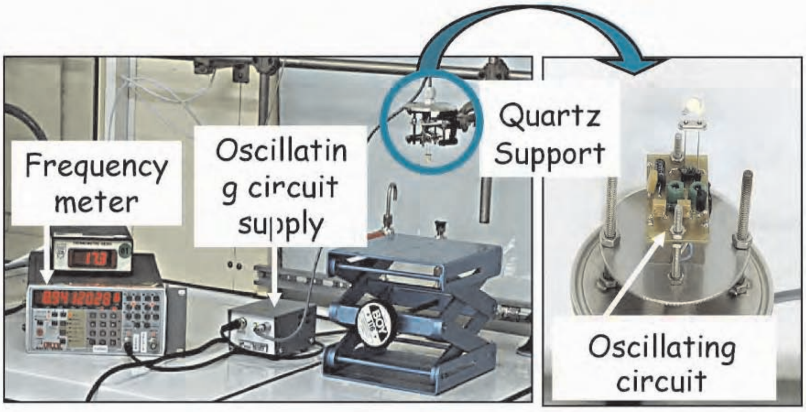
$$\frac{\Delta F}{F_0^{\,2}} = K \times m_{ads}$$

Equation of Sauerbrey



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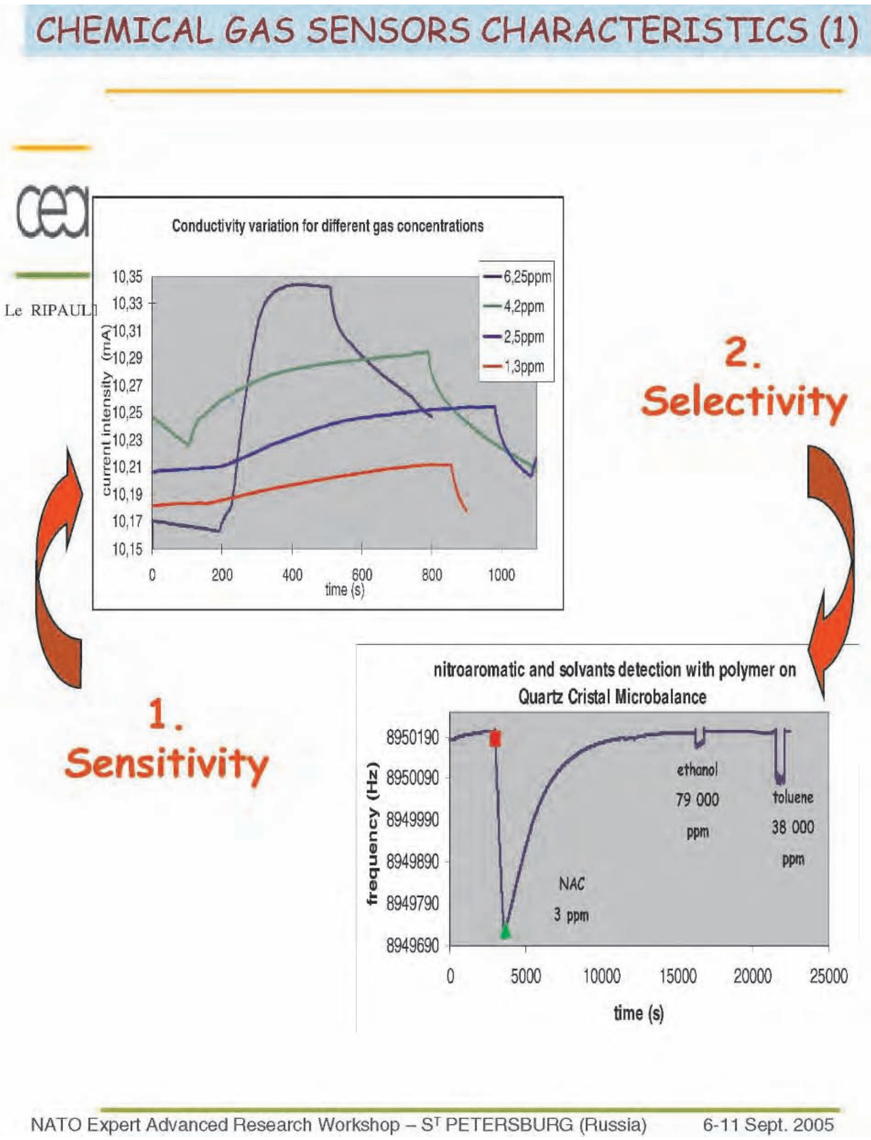

CHEMICAL GAS SENSORS CHARACTERISTICS (1)
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Conductivity variation for different gas concentrations
current intensity (mA)
time (s)
6,25ppm
4,2ppm
2,5ppm
1,3ppm
1. Sensitivity
2. Selectivity
nitroaromatic and solvants detection with polymer on Quartz Cristal Microbalance
frequency (Hz)
time (s)
NAC 3 ppm
ethanol 79 000 ppm
toluene 38 000 ppm
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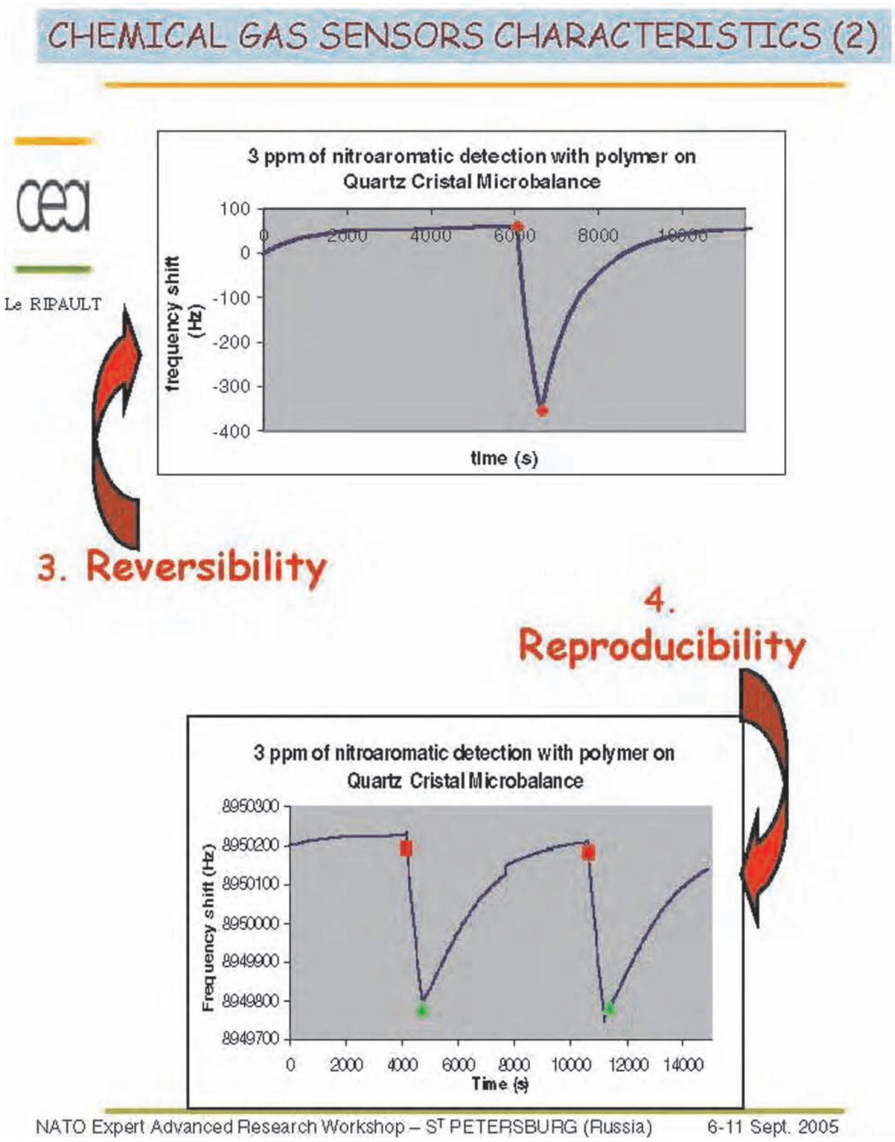
CHEMICAL GAS SENSORS CHARACTERISTICS (2)
cea
Le RIPAULT
3 ppm of nitroaromatic detection with polymer on
Quartz Cristal Microbalance
frequency shift (Hz)
time (s)
3. Reversibility
4. Reproducibility
3 ppm of nitroaromatic detection with polymer on
Quartz Cristal Microbalance
Frequency shift (Hz)
Time (s)
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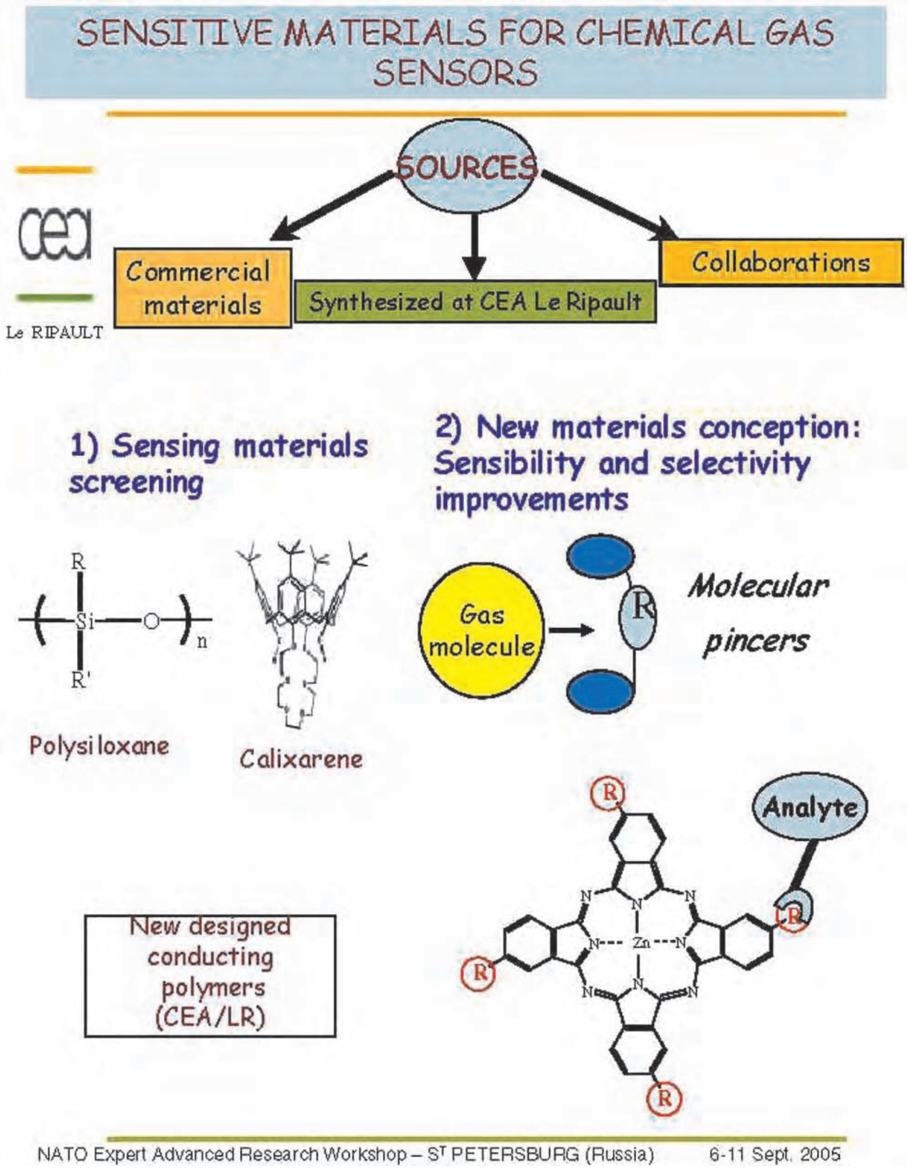
SENSITIVE MATERIALS FOR CHEMICAL GAS SENSORS
SOURCES
Commercial materials
Synthesized at CEA Le Ripault
Collaborations
cea
Le RIPAULT
1) Sensing materials screening
2) New materials conception: Sensibility and selectivity improvements
R
Si
O
n
R'
Polysiloxane
Calixarene
Gas molecule
R
Molecular pincers
Analyte
R
N
Zn
New designed conducting polymers (CEA/LR)
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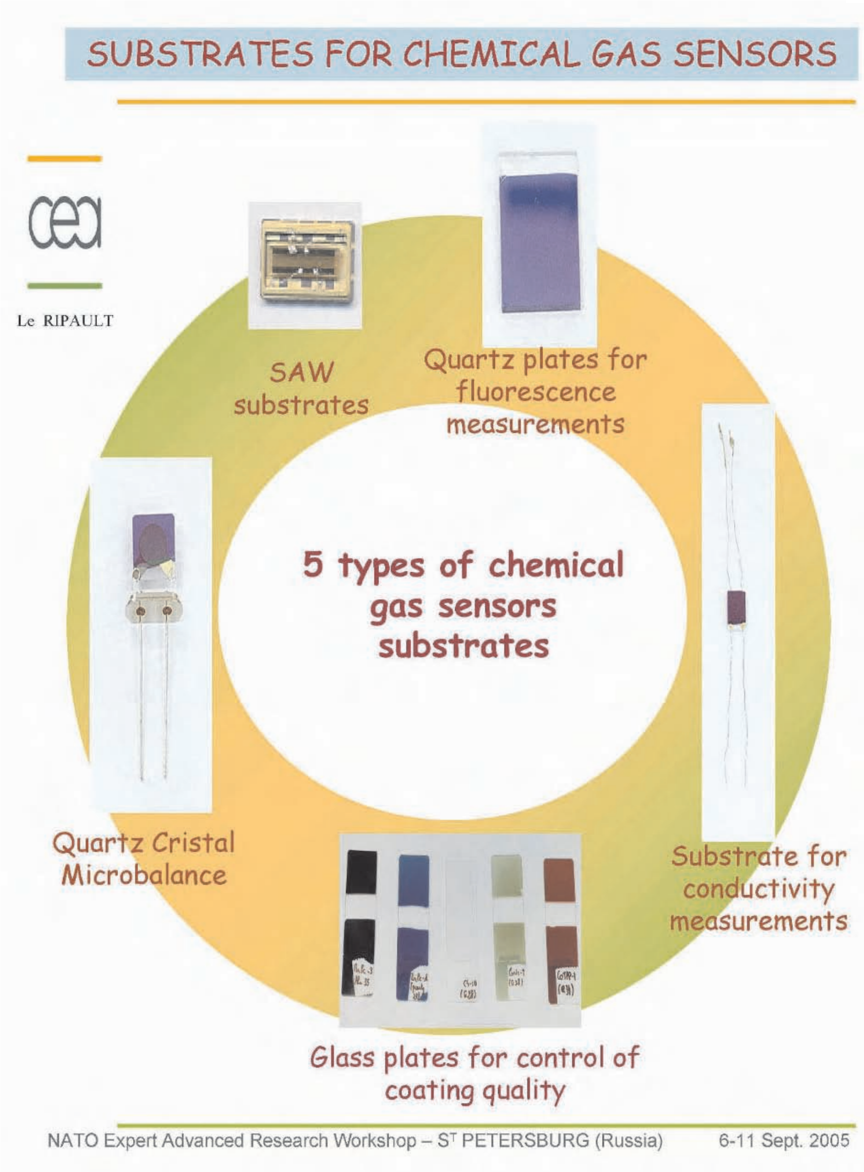
SUBSTRATES FOR CHEMICAL GAS SENSORS
cea
Le RIPAULT
SAW substrates
Quartz plates for fluorescence measurements
5 types of chemical gas sensors substrates
Quartz Cristal Microbalance
Substrate for conductivity measurements
Glass plates for control of coating quality
NATO Expert Advanced Research Workshop – ST PETERSBURG (Russia)
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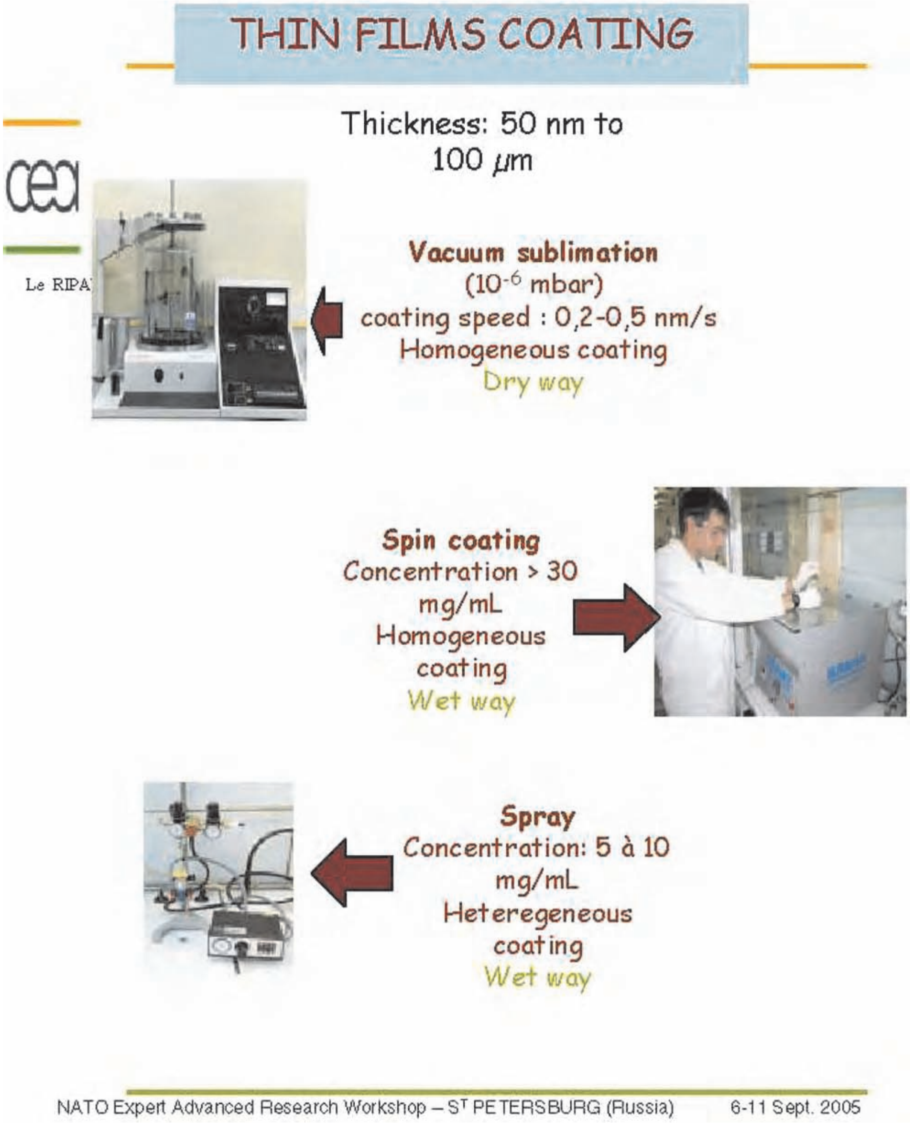
THIN FILMS COATING
Thickness: 50 nm to 100 µm
cea
Le RIPA
Vacuum sublimation
(10-6 mbar)
coating speed : 0,2-0,5 nm/s
Homogeneous coating
Dry way
Spin coating
Concentration > 30 mg/mL
Homogeneous coating
Wet way
Spray
Concentration: 5 à 10 mg/mL
Heteregeneous coating
Wet way
NATO Expert Advanced Research Workshop – ST PETERSBURG (Russia)
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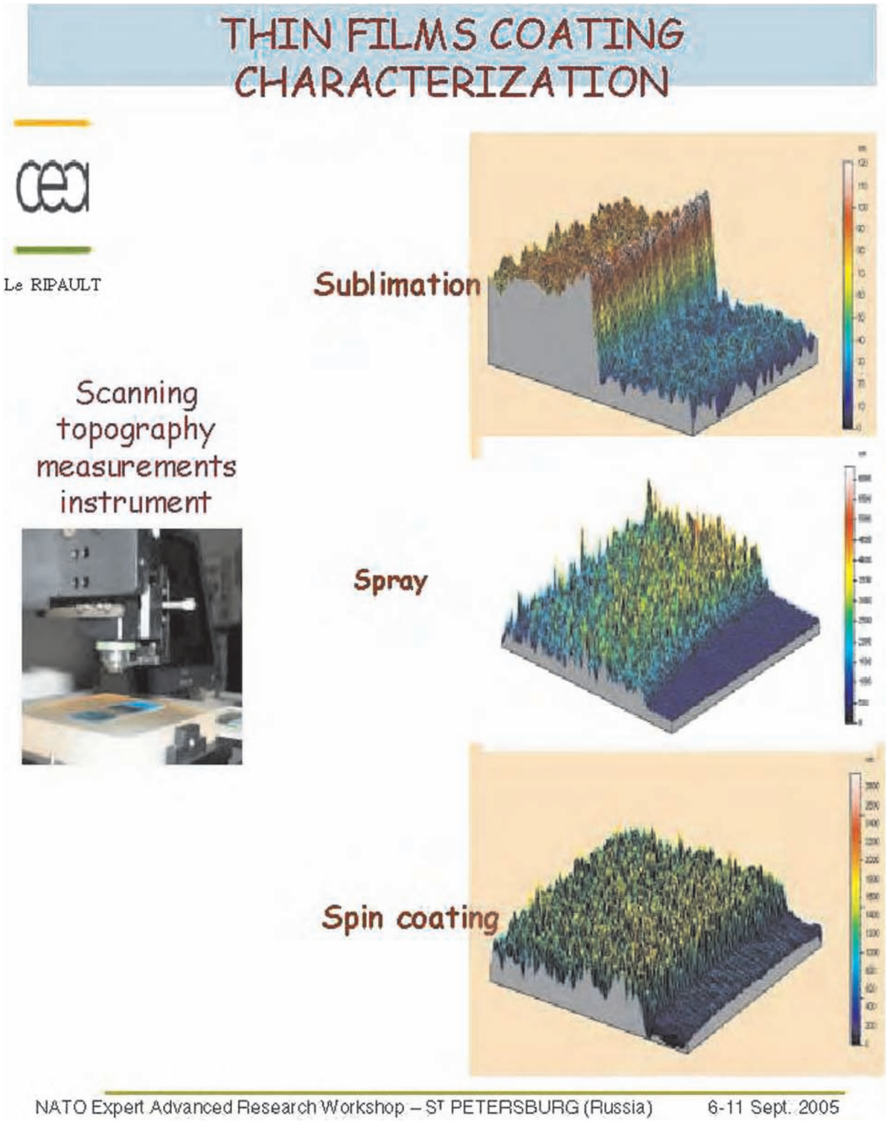
THIN FILMS COATING
CHARACTERIZATION
Le RIPAULT
Scanning
topography
measurements
instrument
Sublimation
Spray
Spin coating
NATO Expert Advanced Research Workshop – ST PETERSBURG (Russia)
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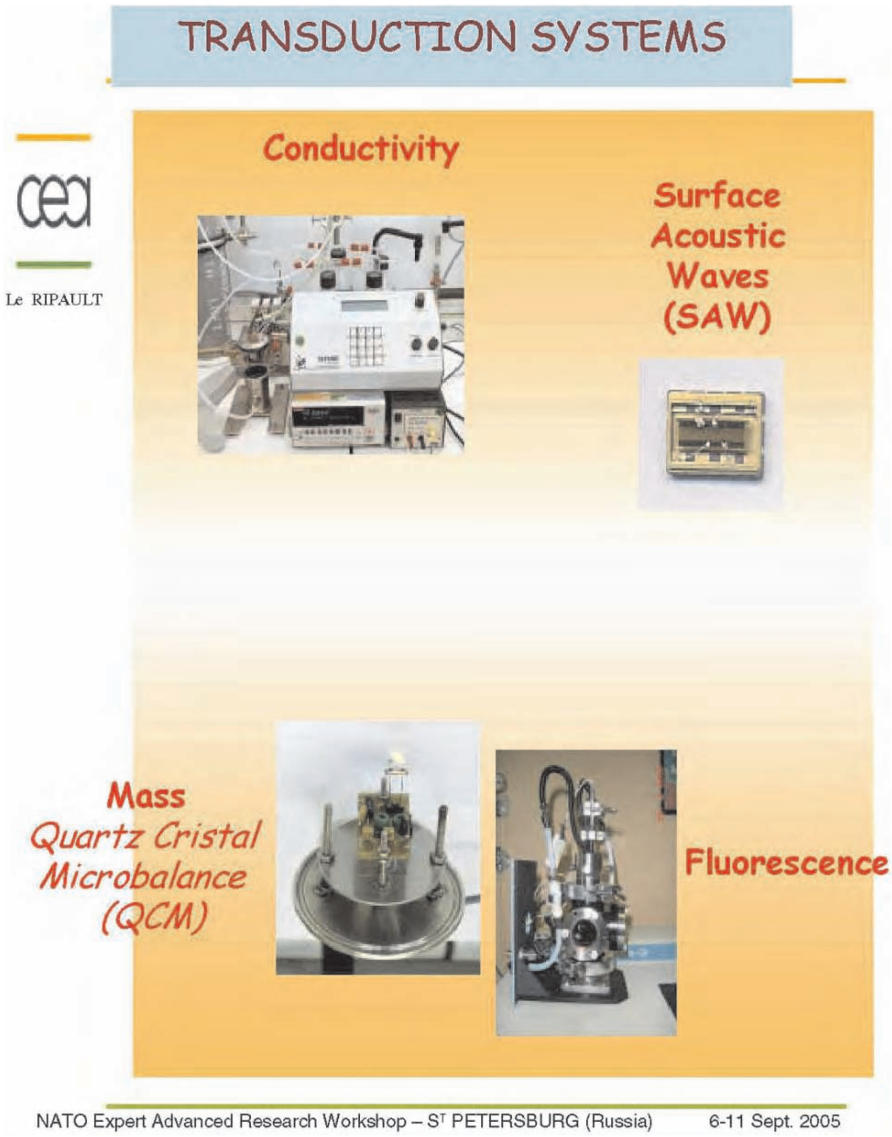
TRANSDUCTION SYSTEMS
Conductivity
Surface Acoustic Waves (SAW)
Le RIPAULT
Mass
Quartz Cristal Microbalance (QCM)
Fluorescence
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GAS GENERATOR AND DILUTER

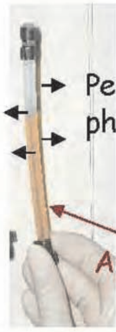
cea

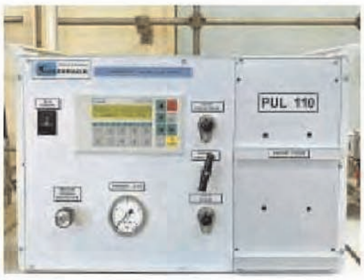
Le RIPAULT

Permeation system:

Permeation tubes contain liquid or solid analyte. Tube's wall in PTFE = flow regulator

- Oven (100 – 200 °C)
- Nitrogen as diluter gas





- **Nitroaromatic Concentration:**

  20 ppb to 1 ppm

- **Flow range: 0 to 50 l/h**

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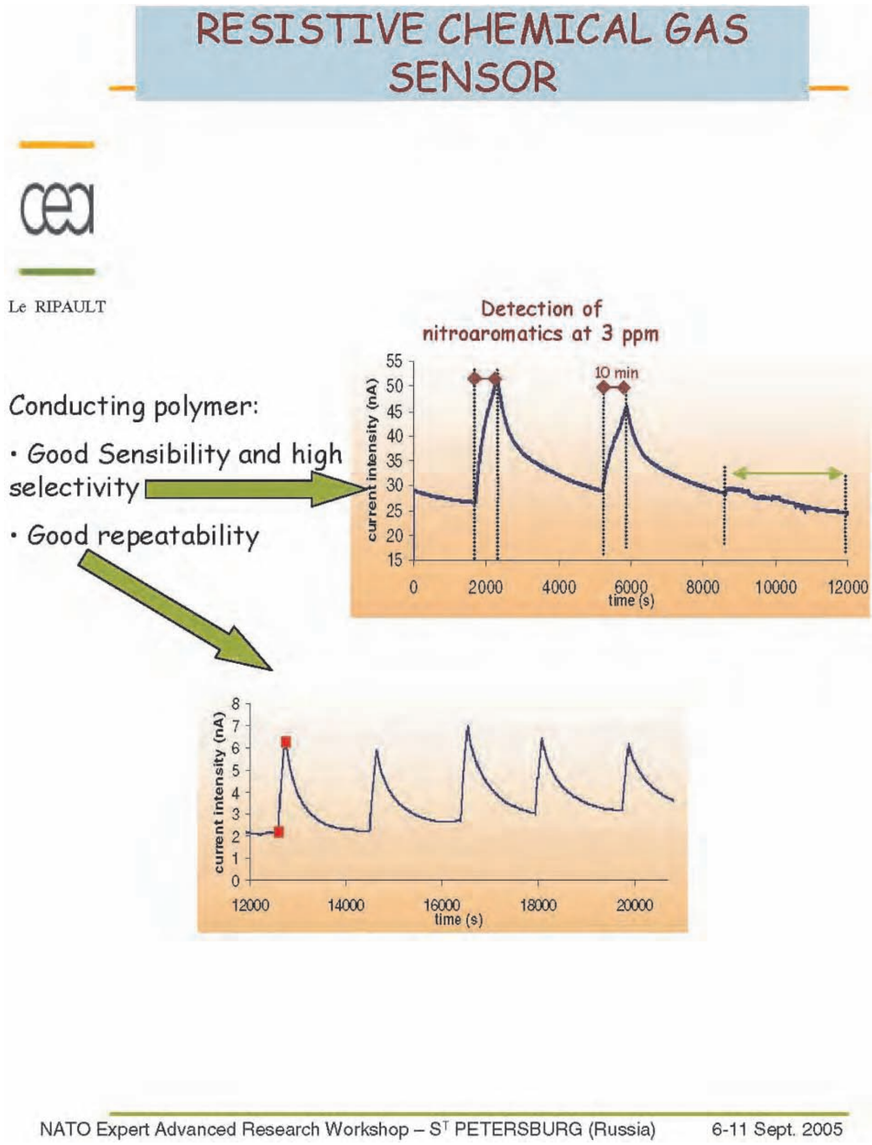
RESISTIVE CHEMICAL GAS SENSOR
Le RIPAULT
Conducting polymer:
• Good Sensibility and high selectivity
• Good repeatability
Detection of nitroaromatics at 3 ppm
10 min
current intensity (nA)
time (s)
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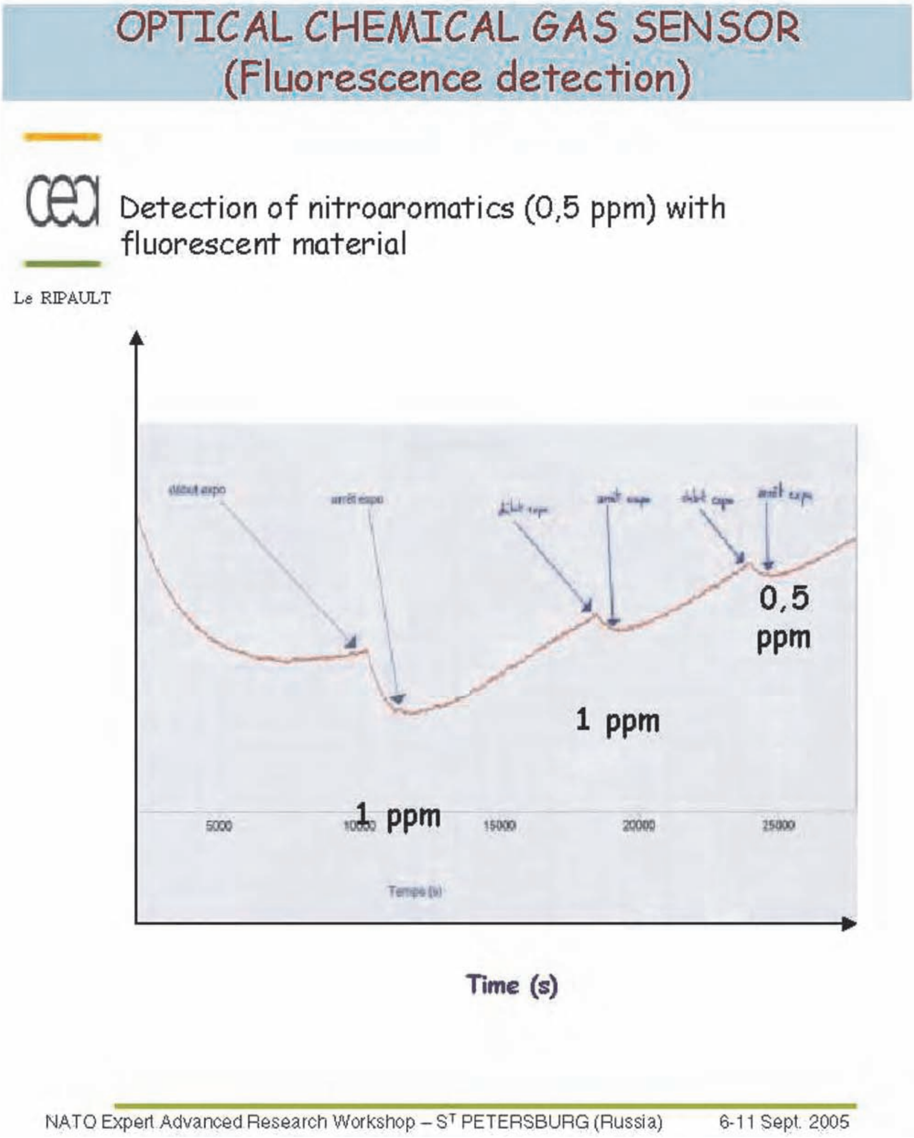
OPTICAL CHEMICAL GAS SENSOR
(Fluorescence detection)
Detection of nitroaromatics (0,5 ppm) with fluorescent material
Le RIPAULT
0,5 ppm
1 ppm
1 ppm
5000
15000
20000
25000
Time (s)
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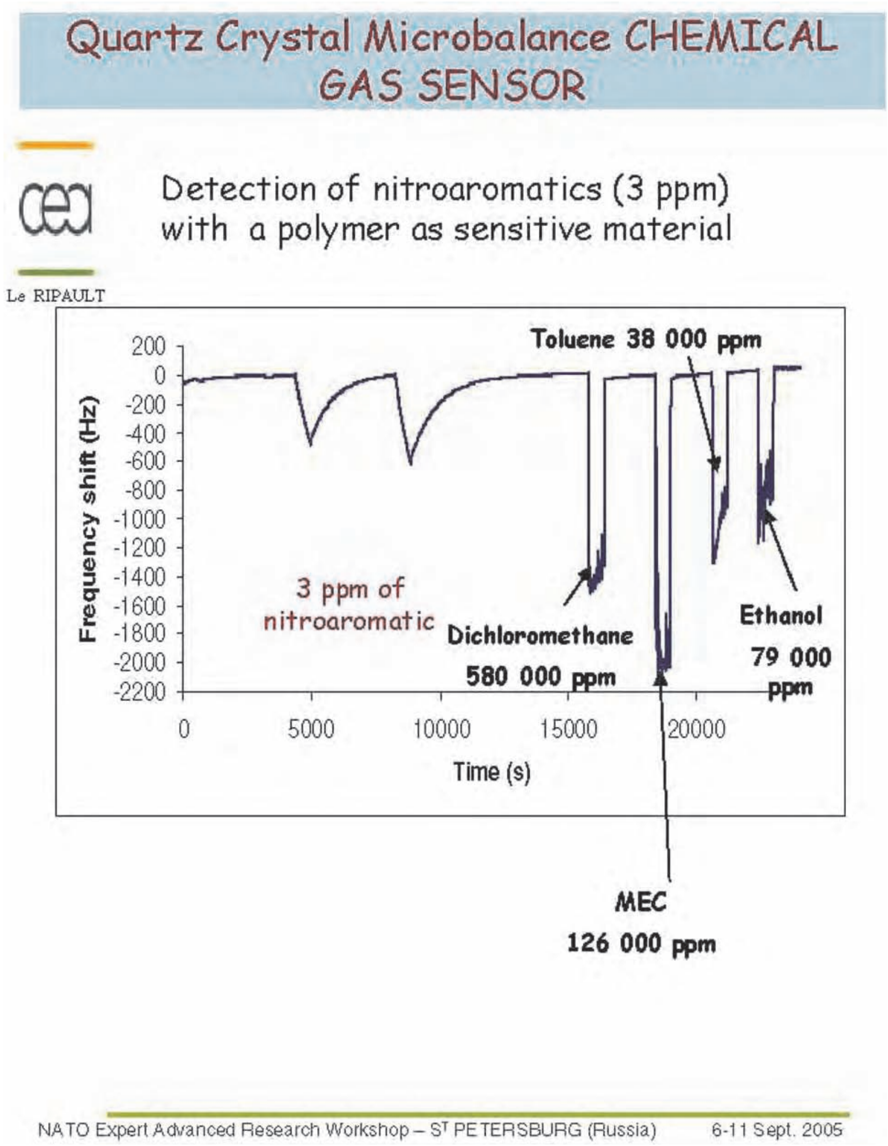
Quartz Crystal Microbalance CHEMICAL GAS SENSOR
Detection of nitroaromatics (3 ppm) with a polymer as sensitive material
Le RIPAULT
Frequency shift (Hz)
200
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
-2000
-2200
0
5000
10000
15000
20000
Time (s)
3 ppm of nitroaromatic
Toluene 38 000 ppm
Dichloromethane 580 000 ppm
Ethanol 79 000 ppm
MEC 126 000 ppm
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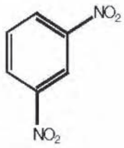
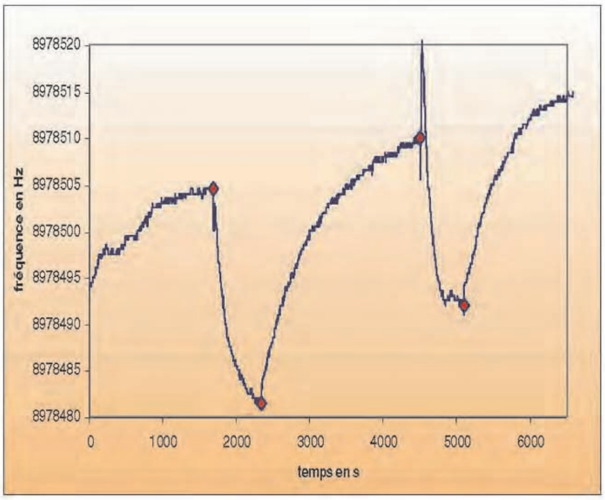
Detection of 150 ppb of Dinitrobenzene with a polymer coated on Quartz Cristal Microbalance





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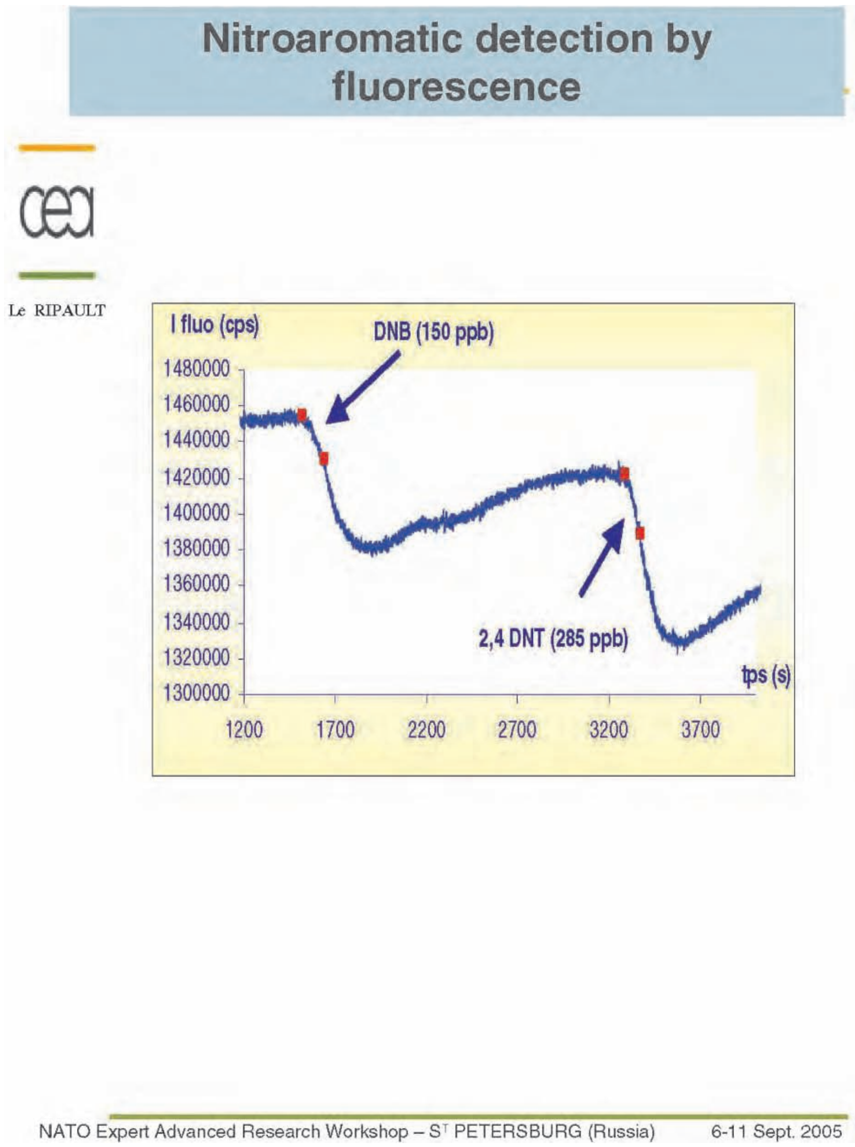
Nitroaromatic detection by fluorescence
Le RIPAULT
I fluo (cps)
DNB (150 ppb)
1480000
1460000
1440000
1420000
1400000
1380000
1360000
1340000
1320000
1300000
2,4 DNT (285 ppb)
tps (s)
1200
1700
2200
2700
3200
3700
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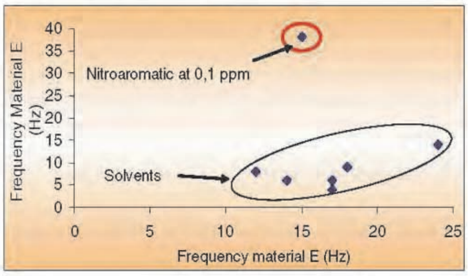
Sensors array

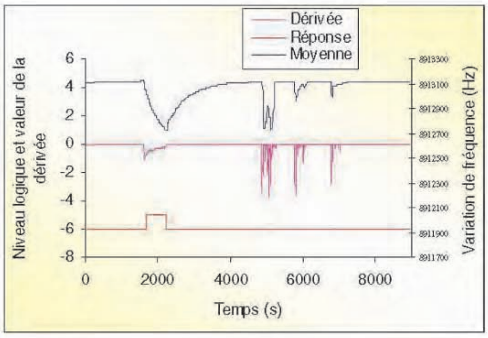
Le RIPAULT

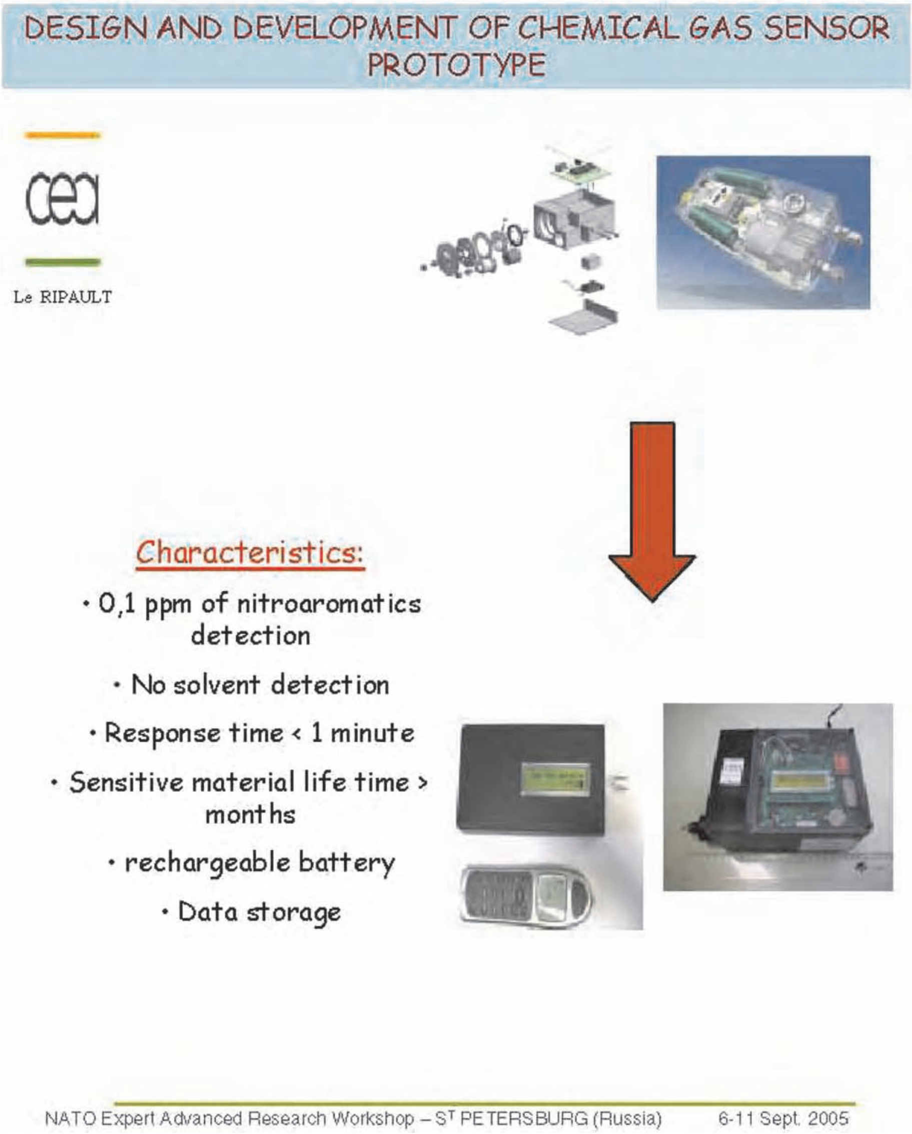


Sensors array technology:

- 8 sensitive materials
- Improvement of global selectivity and robustness
- Possibility to detect several gas with one detector
- Data processing:

Neural networks (Matlab, Neuroone) ...




DESIGN AND DEVELOPMENT OF CHEMICAL GAS SENSOR PROTOTYPE
Le RIPAULT
Characteristics:
• 0,1 ppm of nitroaromatics detection
• No solvent detection
• Response time < 1 minute
• Sensitive material life time > months
• rechargeable battery
• Data storage
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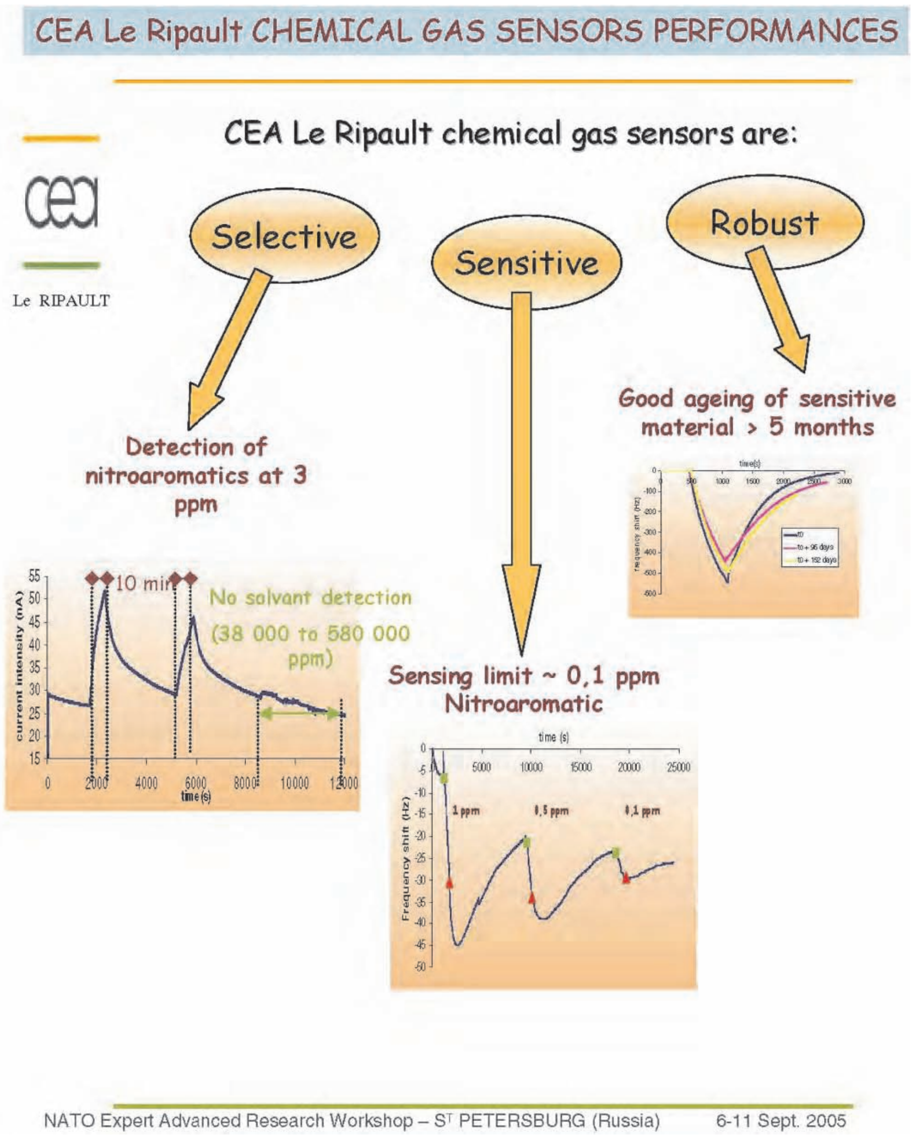
CEA Le Ripault CHEMICAL GAS SENSORS PERFORMANCES
cea
Le RIPAULT
CEA Le Ripault chemical gas sensors are:
Selective
Sensitive
Robust
Detection of nitroaromatics at 3 ppm
10 min
No solvant detection
(38 000 to 580 000 ppm)
current intensity (nA)
time (s)
Sensing limit ~ 0,1 ppm Nitroaromatic
time (s)
Frequency shift (Hz)
1 ppm
0,5 ppm
0,1 ppm
Good ageing of sensitive material > 5 months
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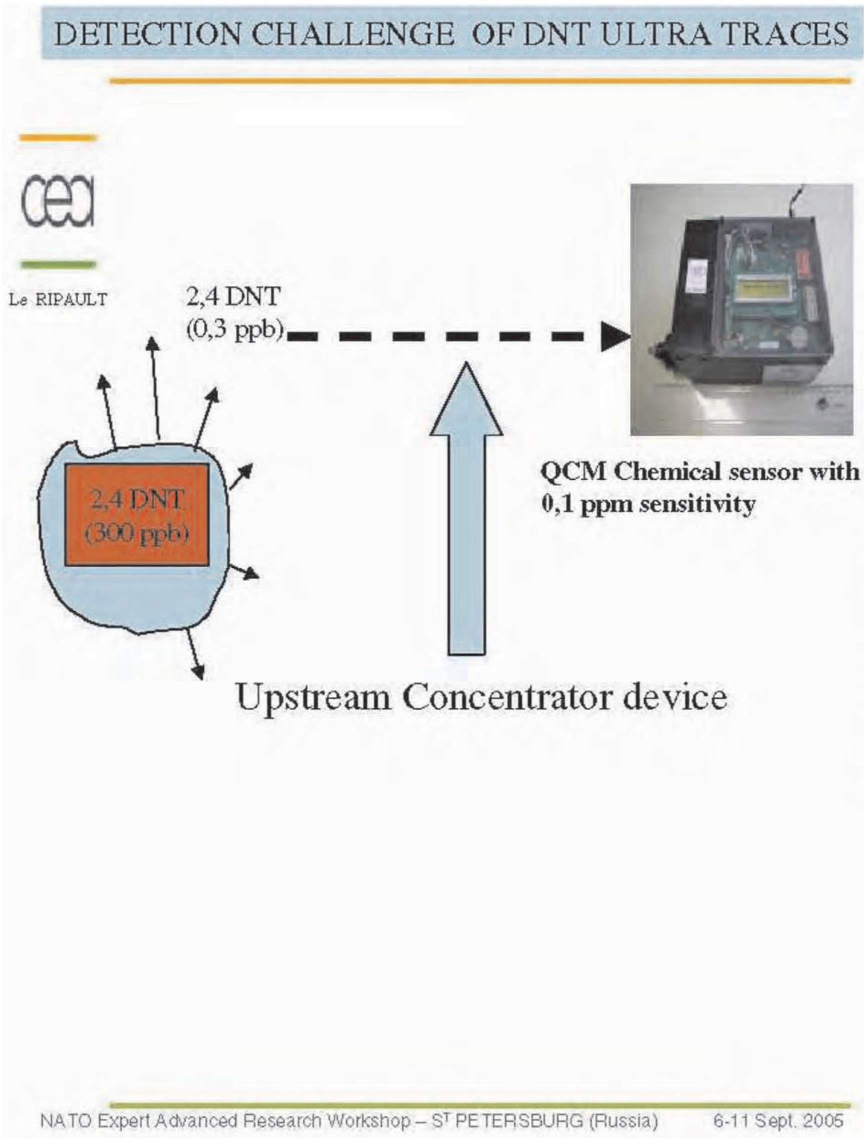
DETECTION CHALLENGE OF DNT ULTRA TRACES
Le RIPAULT
2,4 DNT
(0,3 ppb)
2,4 DNT
(300 ppb)
QCM Chemical sensor with
0,1 ppm sensitivity
Upstream Concentrator device
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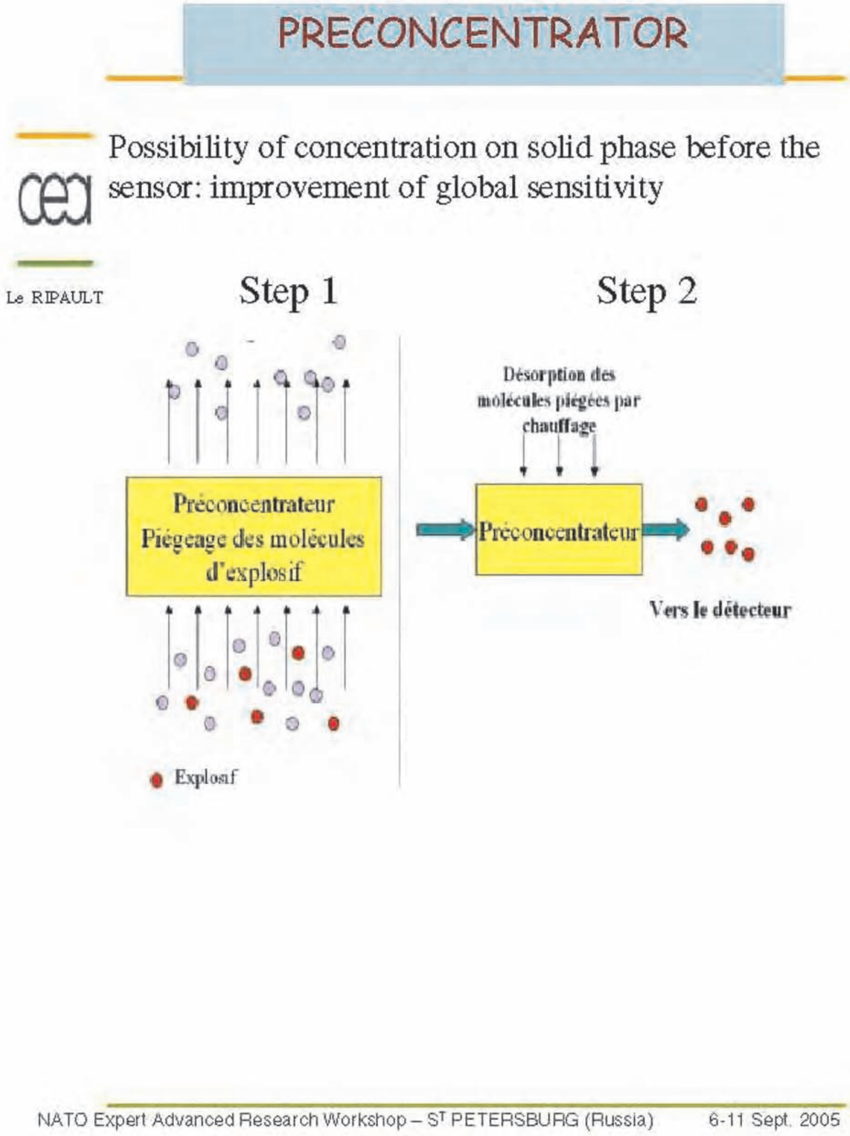
PRECONCENTRATOR
Possibility of concentration on solid phase before the sensor: improvement of global sensitivity
Le RIPAULT
Step 1
Step 2
Préconcentrateur
Piégeage des molécules d'explosif
Explosif
Désorption des molécules piégées par chauffage
Préconcentrateur
Vers le détecteur
NATO Expert Advanced Research Workshop – ST PETERSBURG (Russia)
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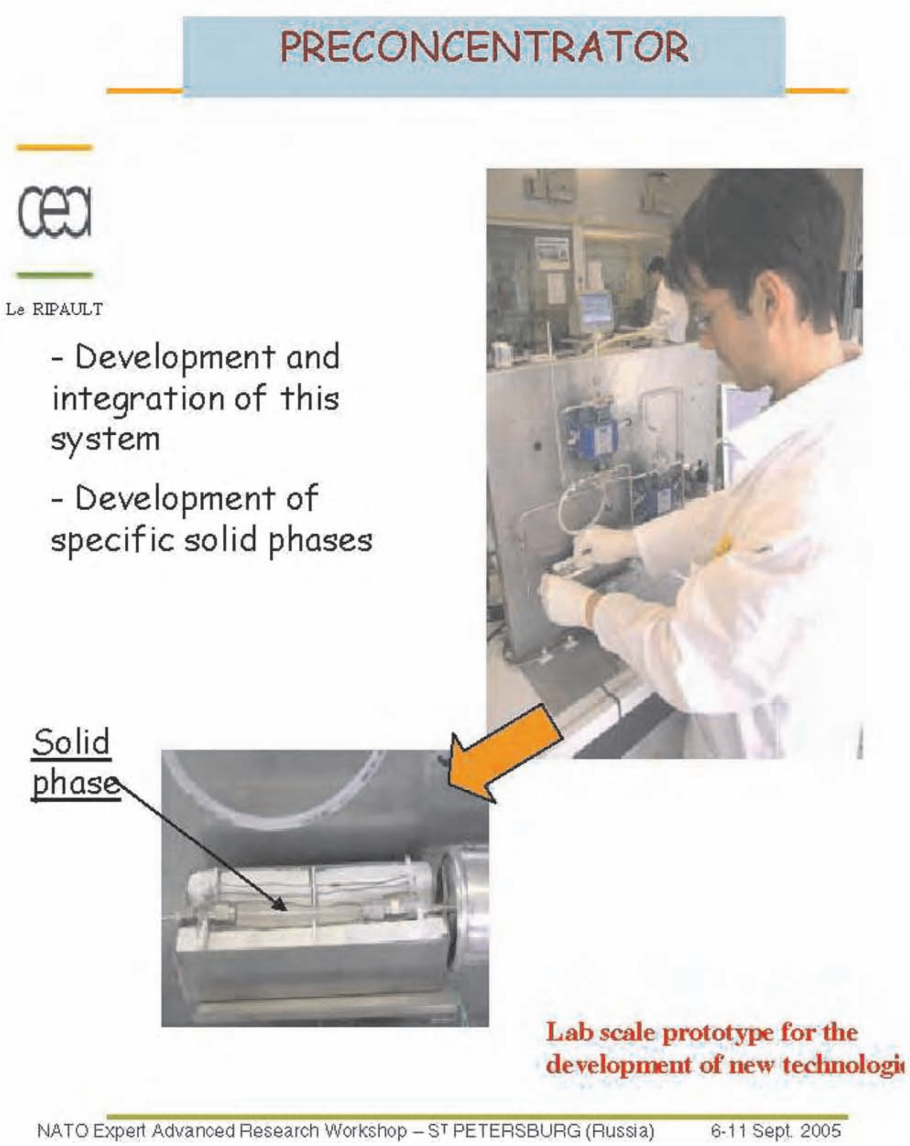
PRECONCENTRATOR
Le RIPAULT
- Development and integration of this system
- Development of specific solid phases
Solid phase
Lab scale prototype for the
development of new technologi
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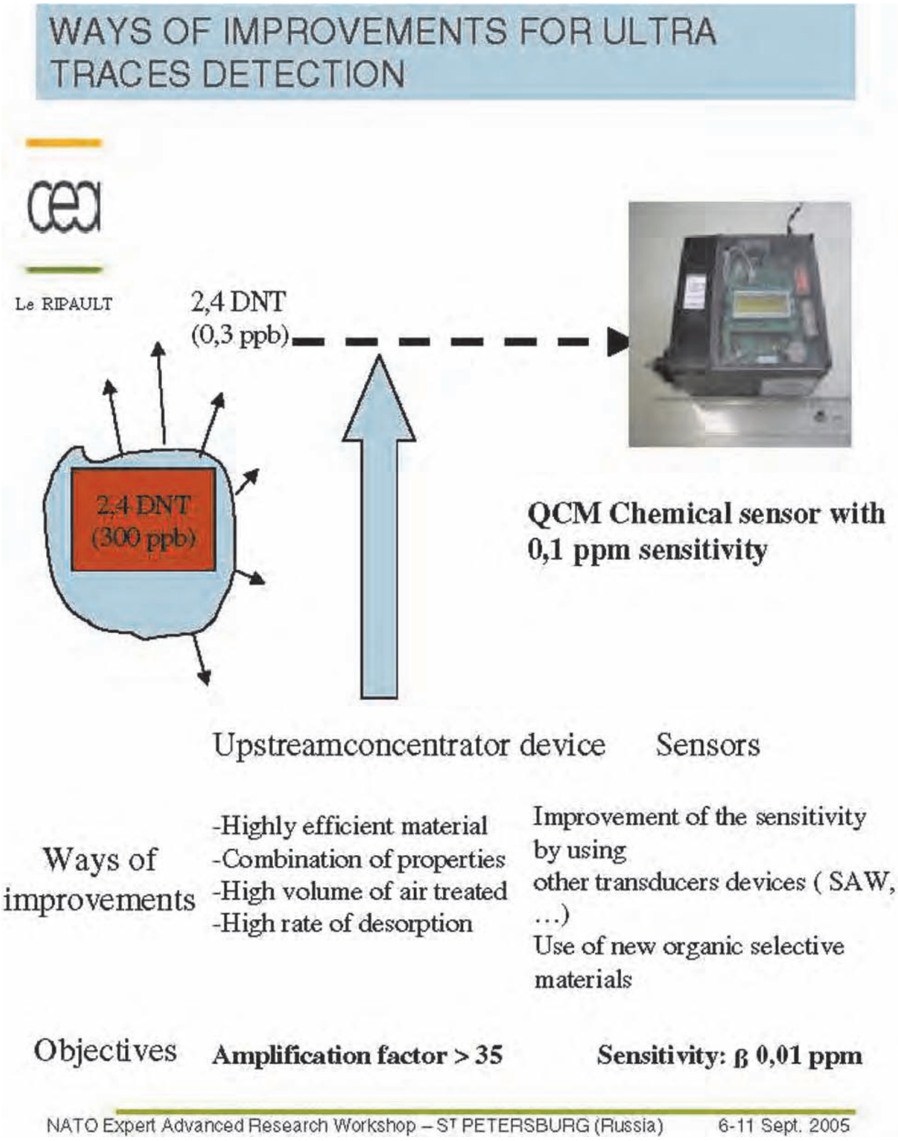
WAYS OF IMPROVEMENTS FOR ULTRA TRACES DETECTION
cea
Le RIPAULT
2,4 DNT
(0,3 ppb)
2,4 DNT
(300 ppb)
QCM Chemical sensor with
0,1 ppm sensitivity
Upstreamconcentrator device
Sensors
Ways of improvements
-Highly efficient material
-Combination of properties
-High volume of air treated
-High rate of desorption
Improvement of the sensitivity by using
other transducers devices (SAW, …)
Use of new organic selective materials
Objectives
Amplification factor > 35
Sensitivity: ß 0,01 ppm
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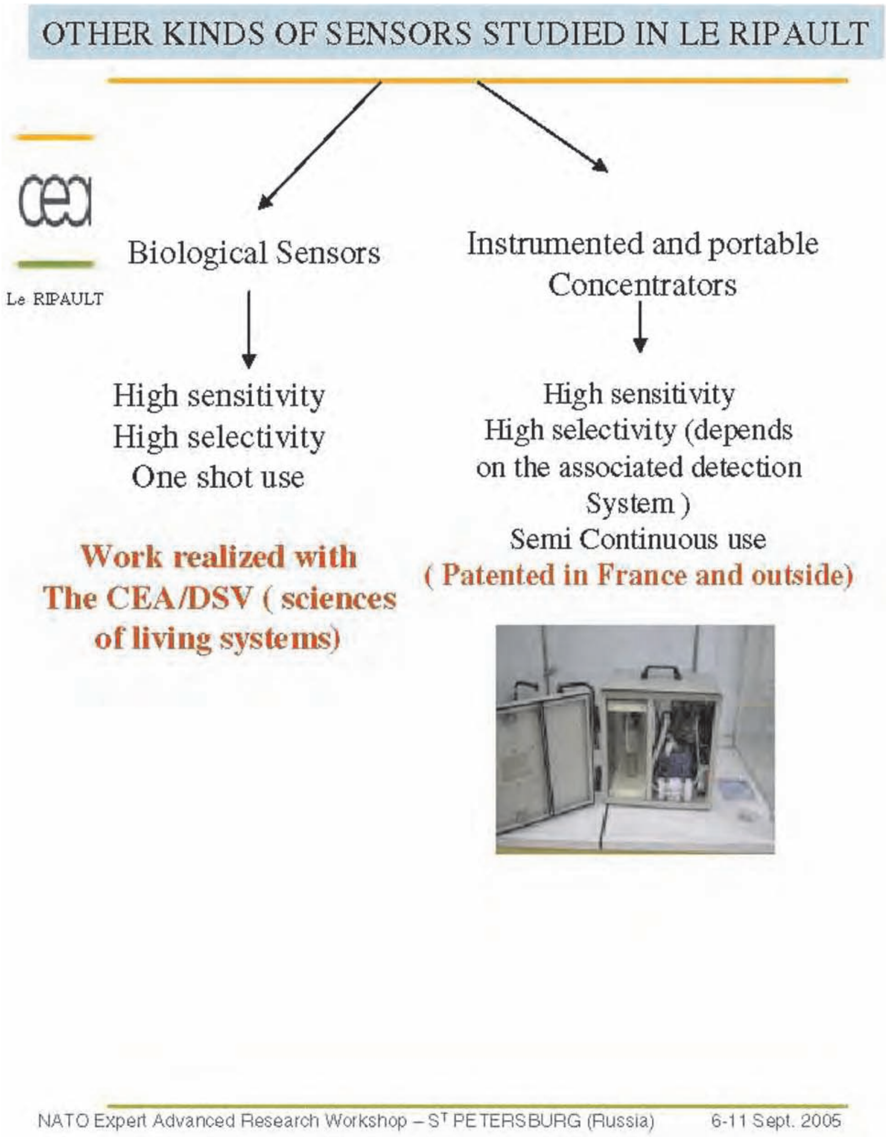
OTHER KINDS OF SENSORS STUDIED IN LE RIPAULT
Le RIPAULT
Biological Sensors
Instrumented and portable
Concentrators
High sensitivity
High selectivity
One shot use
High sensitivity
High selectivity (depends
on the associated detection
System)
Semi Continuous use
Work realized with
The CEA/DSV (sciences
of living systems)
(Patented in France and outside)
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Le RIPAULT

Conclusions

- Explosives detection is a very extended field with very different competences needed to reach ambitious objectives in term of detection threshold challenge and reliability of the systems.
- CEA/LE RIPAULT has developped a large and complete capability of techniques to create and develop sensors

  for explosives detection and other targets .
- The performances we try to obtain from our technology

  is the best compromise between :
  - Sensitivity
  - Time of response (continuous or discontinuous)
  - Portability (fast handling use sensor device)
  - Selectivity (to reduce the number of false alarms)
  - Life duration

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OBJECTIVES FOR THE NEAR FUTURE AND LATER ….

Le RIPAULT

- Improvement of the Technologies Developed up to Now to Reach more Sensitive, fast handling and Reliable Systems,

- Work on others Targets : « Homemade Explosives », …

- To Extend our Collaborations Network to Benefit of the Synergies of this very Active Domain :

- European Collaboration (Detex Project in progress)

- Collaboration with Foreign Labs .

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DETECTION OF EXPLOSIVES BY QUADRUPOLE RESONANCE METHOD: NEW ASPECTS FOR SECURITY

T.N. RUDAKOV*, T.J. RAYNER, P.A. HAYES,
K.L. RUSSETH
QRSciences Limited, Cannington, Australia.

1. Introduction

A very important part of aviation security is the detection and identification of explosives in baggage. There are many detection techniques employing a range of different technologies that are based on physical and chemical properties of such substances. At present the most widely used screening technique employs transmission X-ray imaging. The method is based on the irradiation of baggage by X-rays and receiving transmitted radiation in order to determine the presence or not of a weapon or explosive. X-ray machines used at checkpoints offer excellent image quality, and with a skilled operator, a high probability of detection for a range of both explosive and non-explosive threats. However the detection technique on the basis of X-rays has a relatively low sensitivity of certain configurations of explosives.

The nuclear quadrupole resonance (NQR) method, often referred to as QR, provides automated detection of explosives types in configurations missed by the imaging X-ray method. Therefore combining QR technology with existing X-ray systems can provide improved scope for the checkpoint detection of explosive threats.

The QR method is a radio-frequency (RF) spectroscopic technique that can be used for a number of applications in particular in detecting crystalline materials such as modern plastic explosives. Since the NQR frequencies depend on the molecular structure of these substances they can be used for their practically unique detection and identification. For example using the QR method it is possible to detect plastic explosives containing RDX, PETN, HMX, tetryl, TNT, ammonium nitrate (AN),

* E-mail: trudakov@qrsciences.com

H. Schubert and A. Kuznetsov (eds.), Detection and Disposal of Improvised Explosives, 191–204.

ammonium perchlorate, peroxides (such as HMTD) and others. Mixed explosives such various grades of Semtex are readily identifiable from their chemical mixture also. The QR method is very similar to the well-known nuclear magnetic resonance (NMR) method and therefore can operate with a very low false-alarm rate (FAR). However unlike NMR, QR does not require an expensive magnet and is therefore relatively inexpensive and more compact.

QRSciences, a leader in the development of QR based explosive detection systems (EDS) has developed advanced QR baggage screening machines for use primarily in airports. The operational capabilities of these units were positively assessed by the TSA Transportation Security Laboratory/FAA Tech Center near Atlantic City, USA and other authorities in many countries. The units were shown to be effective in the detection of dangerous quantities of various types of explosives in typical baggage sets.

In this paper we offer an analysis of some issues specific to the QR detection of explosives. We discuss the QR detection techniques developed for different explosive substances. We also present some interesting QR parameters obtained by our research group for a number of investigated explosive substances. In this report the operational features of a QR machine are presented. The basic design, performance and some characteristics of advanced NQR machines for baggage screening are reported. These machines operate effectively in the real world conditions. This was verified by a number of independent trials over a range of explosive substances.

2. QR Method for Explosive Detection

The QR method is closely related to NMR based Magnetic Resonance Imaging (MRI), widely employed by both industry and the medical profession. In NMR, however, the energy levels are primarily dependent on the coupling of the nuclear magnetic moment to the external magnetic field whereas in NQR no external magnetic field is required to establish the energy levels. In NQR atomic nuclei with a non-spherical charge distribution (a nuclear spin $I \geq 1$), which possess nonzero electric quadrupole moment, interact with the local inhomogeneous electric field or the electric field gradient (EFG) produced by nearby charges. This interaction removes the degeneracy of the nuclear ground state and establishes the nuclear quadrupole levels with different energy. The transition frequencies between the energy levels depend both on the nuclear quadrupole moment, which is a property of the nucleus, and the EFG tensor, which is determined by the electric charge distribution around the nucleus. The QR frequencies thus are very sensitive to the molecular

structure of the substances and can be used for their identification. Therefore a key advantage of QR is that a magnetic field is not required to create magnetization because the electric quadrupole moments of the nuclei interact with the internal electric field gradients of the surrounding charges in molecules. That makes QR technology to be a simpler, less costly and more efficient platform technology.

The first important application for the QR technology is aimed at fixing a major deficiency in the carry-on/carry-in baggage screening market, namely the ability to detect sheet and distributed plastic explosives, as the method is sensitive to the chemical structure of the explosives and independent of their configuration. Therefore QR method provides a highly specific and arguably unique frequency signature for such materials. Most explosives contain quadrupolar nuclei, for example the nitrogen (14N) nuclei the spectral lines of which are usually located at RF frequencies (0.4-6MHz). The explosives pose the specific QR frequencies and different relaxation parameters which must be taken into consideration when choosing an optimal technique.

Besides the QR technology is quite safe and successfully trialled by authorities worldwide. The detection process is automated so no reliance on operator vigilance or skill is required. The QR technology is non-disruptive to normal screening operations. QR is complementary and adds important functionality to all currently deployed X-ray systems. Explosives can be automatically detected regardless of size, shape, weight or bag clutter.

There are also follow-on opportunities in the explosive detection market to screen cargo, people and mail (Figure 1). Moving in these directions is the next phase of expansion of QR technology:

- Transportation – rail, subways, buses & cargo trains, etc.
- Commerce – freight, parcels, mail, mailrooms and delivery services.
- Facility & Event Protection – corporate foyers, cultural & entertainment venues, government buildings etc.
- Critical Infrastructure – utilities, power plants, water treatment facilities

At the moment the most important application of QR method is aviation security. In this area QR based machines are used can be used for baggage and people screening. Figure 2 shows a diagram demonstrating the main categories of QR machines for baggage screening.

A similar diagram for people screening is presented in Figure 3. Two different QR techniques can be applied to detect explosives, either using large volume coils, or remote (or one-sided) detection using special coils. In the first case one coil is normally used for both irradiating and receiving. In

remote QR, flat surface coils (antennae) are used, and irradiating and receiving coils are sometimes separated.

Figure 1. Main applications of QR explosive detection technology.

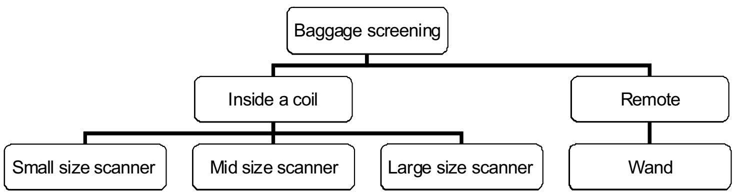


Figure 2. QR techniques for baggage screening.

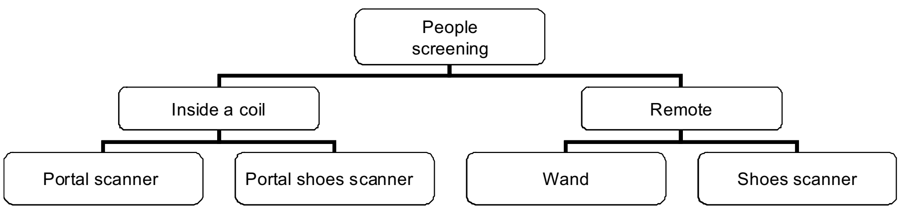


Figure 3. QR techniques for people screening.

When using QR method for explosive detection a relatively poor signal-to-noise ratio (SNR) is often an issue [1]. In order to improve sensitivity it is common to employ multi-pulse techniques, special equipment and signal processing [2].

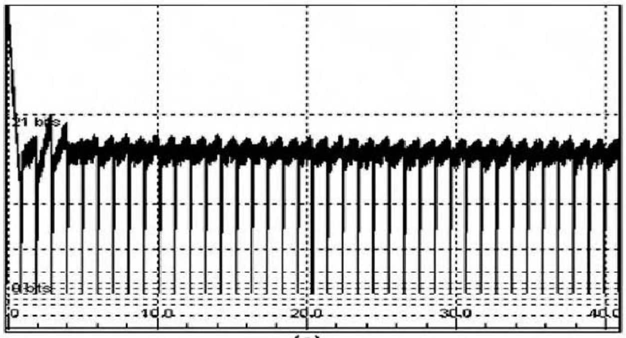
3. Multi-pulse QR Technique for Explosive Detection

A choice of the optimal pulse sequence is to a great extent determined by fixed parameters related to the QR "nature" of the explosive such as QR frequencies and relaxation times. These parameters vary considerably for different substances, and the most effective RF pulse sequence that maximizes the SNR per unit time is selected for each substance. Another important purpose of pulse sequences is to provide good elimination of spurious RF signals, which cause false alarms. The effect of various pulse sequences on the quadrupolar nuclei was investigated both theoretically and experimentally taking into account the difference between the NMR and NQR spin-systems [3-10]. Here we present only a brief description of pulse sequences used for explosive detection and a general approach to designing them.

In general we can divide all pulse sequences into two main groups: the Steady-State Free Precession (SSFP) type multi-pulse sequences and the Spin-Locking Multi-Pulse (SLMP) sequences. The first group of sequences produces a relatively large and continuous steady-state signal, which recurs for as long as the sequence is applied. These sequences are very effective for detection of explosives with short spin-lattice relaxation time T1, such as RDX. A typical QR signal obtained with this kind of sequence is presented in Fig. 4a.

The second group of sequences causes a refocusing of transverse magnetization for periods much longer than the T2 time. These sequences are very effective in the case when the detection time is close to or shorter than T1. In order to achieve high sensitivity it is necessary to ensure that the value of the decay constant of QR signals (effective time T2e) for the sequence is as close to T1 as possible. This may be accomplished at short time intervals between pulses. It is also desirable that the detection time does not exceed the T2e time because the signal to noise ratio will degrade. In practice it is not hard to meet all these conditions. The SLMP sequences are normally used for detection of explosives with long T1, for example PETN. Fig. 4b demonstrates a typical QR signal obtained with an SLMP sequence.

The effectiveness of a pulse technique strongly depends on parameters of the sequence, for example the pulse duration, pulse spacing and pulse



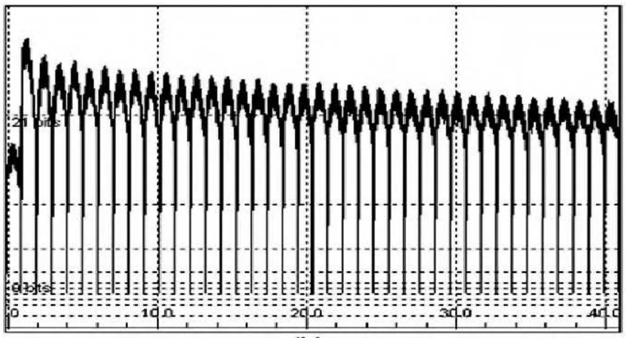


Figure 4. A typical QR signal (magnitude) obtained with: (a) SSFP type sequence, (b) SLMP type sequence.

phase. Therefore in order to achieve high sensitivity it is necessary to find the optimal value of these parameters for specific detection conditions.

Pulse sequences are also used to provide good elimination of spurious RF signals. In practical situations the investigated baggage can contain objects which, when irradiated with strong RF pulses, can become sources of coherent spurious signals (coherent noise): magneto-acoustic and/or piezoelectric ringing. These spurious signals could be very strong and are the main reason for the false alarm rate (FAR) for explosive detection systems. A general approach to rejection of spurious coherent RF signals includes accumulation of the total signal and the signal without a contribution from the quadrupolar nuclei and the subtraction of the latter from the former. Therefore a multi-pulse method is comprised of applying at least two excitation sequences. The first sequence is intended for the excitation of the QR signal and coherent noise together, and the second one – for the excitation of coherent noise only. In order to avoid detecting a QR signal in the second block, a certain delay is set between the two blocks and/or the spin-saturation technique or a phase flip is applied.

If the structures of the first and the second blocks are identical, this method ensures very efficient coherent noise elimination even in the case of low frequencies. Unfortunately the behavior of the spurious signals is unpredictable before excitation and two blocks are not always effective for cancellation. The problem is solved by using more complicated detection technique, which includes additional subtraction blocks and/or previous irradiation of the items on a close frequency. The effectiveness of this technique for the rejection of the coherent spurious signals and distinguishing the QR signal is clearly demonstrated in Figures 5 and 6. It should be noted that this technique is successfully used in the current QRSciences explosive detection systems.

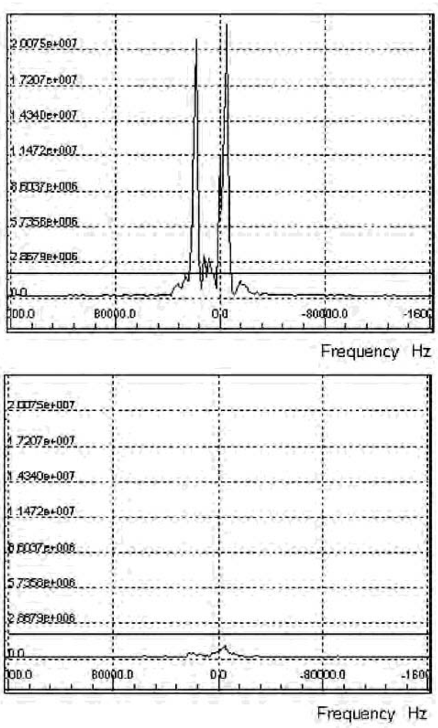


Figure 5. A coherent spurious signal from an umbrella detected in the baggage scanner coil using: (a) conventional pulse sequence, (b) special pulse sequence. The frequency is 600 kHz.

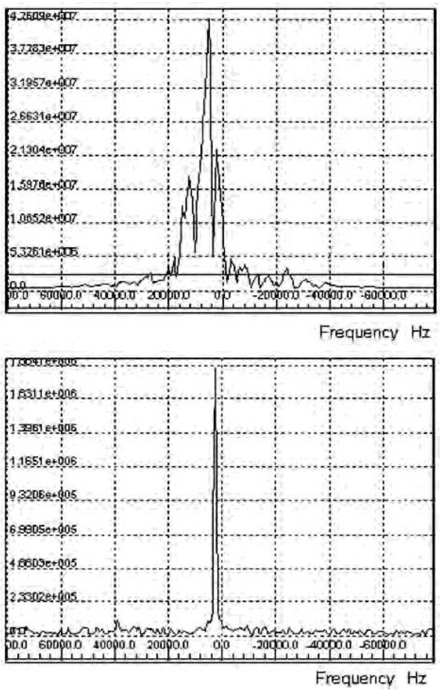


Figure 6. Eliminating the spurious signal (a) A coherent spurious signal from an umbrella together with the QR signal from PETN detected in the baggage scanner coil using a conventional pulse sequence. The QR signal cannot be seen. (b) Separating the QR signal from the coherent noise by using a special pulse sequence.

4. Extension of Explosive Detection Capabilities

At the moment the QRSciences baggage scanners are designed to be able to detect RDX, HMX and PETN based explosive materials including any plastic, powder, sheet and bulk explosives. Detection technique for other explosives such as ammonium nitrate (AN), black powder (KNO_3 component) and TNT has also been developed in our laboratory and will be used in subsequent QR scanner systems.

In this paper we introduce some NQR parameters of interest for AN, KNO_3 and TNT obtained by our research group. All relaxation parameters, signal intensity, line widths and temperature coefficients for two lines of nitrogen atoms in the NO_3 group for pure AN and "Powergel" ANFO are presented in Table 1.

Both substances have been successfully detected in actual tests in a 160-liter coil. The detection time did not exceed a few seconds. The results are demonstrated in Figure 7.

Table 1. NQR parameters of ammonium nitrate (NH_4NO_3) at room temperature. (296K).

Frequency kHz	Relative intensity	Line width Hz	T_2^* ms	T_2 ms	T_1 s	Temperature coeff. K_t Hz/degree(K)
ν_+ 497	1.0 (0.4)**	250	1.2(0.9)*	6	12	~ - 30
ν_- 424	0.5 (0.2)**	240	1.6	4.0	16	~ + 100

The same parameters for KNO_3 and Black Powder, which contains 60% of KNO_3 are presented in Table 2. There are two quadrupolar nuclei in KNO_3, and both of them can be used to detect this substance. The intensity of the QR signal in KNO_3 is quite strong which results in a very good detectability of Black Powder.

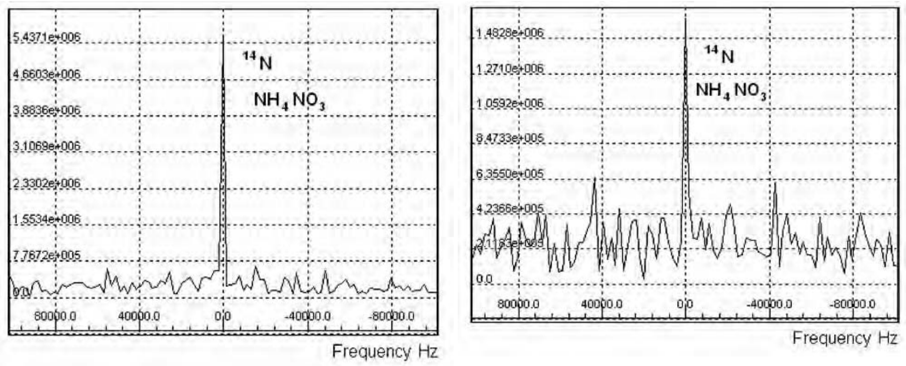


Figure 7. Spectral intensity curve for 497 kHz line obtained in a 160-liter coil with an SLMP sequence for: (a) 500g of pure AN, (b) 500g of “Powergel” ANFO.

Table 2. NQR parameters of potassium nitrate (KNO_3) and Black Powder at room temperature.

Frequency kHz	Relative intensity	Line width Hz	T_2^* ms	T_2 ms	T_1 s	Temperature coeff Kt Hz/degree(K)
664 (^{39}K)	1.0 (0.3)*	650	0.5	5.0	1.0	~ - 350
567 (^{14}N) (ν_+)	1.1 (0.32)*	200	1.6	5.0	8.0	~ - 160
559 (^{14}N) (ν_-)	0.9 (0.26)*	200	1.6	5.0	12.0	~ - 160

* Black powder.

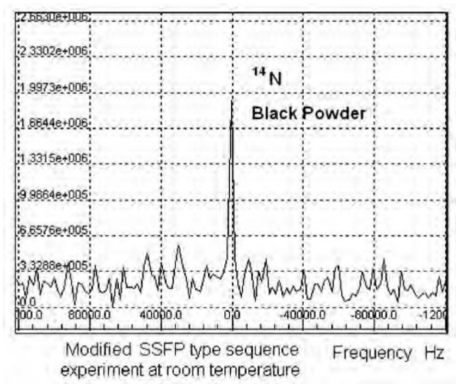


Figure 8. Spectral intensity curve for 567 kHz line obtained in a 160-liter coil with an SLMP sequence for 500g of Black Powder.

Table 3. NQR parameters of orthorhombic TNT at room temperature.

Frequency kHz	Relative intensity	Line width kHz	T_2^* ms	T_2 ms	T_1 s
868	0.78	1.86	0.17	5.0	5.0
861	0.87	1.86	0.17	5.7	12.0
848	0.72	1.6	0.2	5.0	6.0
846	0.9	1.6	0.2	5.4	15
841	1.0(0.15)*	1.6	0.2	6.5	9
837	0.88	1.6	0.2	5.8	6
768	0.37	1.75	0.18	4.0	7
752	0.34	1.6	0.2	2.5	6
741	0.69	1.5	0.21	2.2	8
716	0.3	0.8	0.4	3.0	10
712	0.26	0.8	0.4	3.5	10

The detection of TNT with the QR method is complicated by the existence of at least two polymorphic forms, monoclinic and orthorhombic, which have different QR properties. Further complications are caused by the multi-line spectrum and a very small QR signal-to-noise ration. Nevertheless this substance can be detected with the QR technique [12]. Some parameters of TNT manufactured in Australia - orthorhombic TNT - are presented in Table 3.

Figure 9 demonstrates the detection of TNT in a 1-liter laboratory coil. The detection time did not exceed a few seconds.

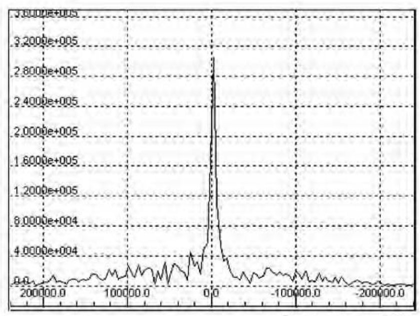


Figure 9. Spectral intensity curve for 741 kHz line obtained in a 1-liter coil with an SLMP sequence for 600g of TNT.

5. New Generation of QR Baggage Scanners

QRSciences has made significant progress in developing multi-technology explosives detection baggage screening platforms including X-ray/QR/metal detector systems. These offer complete explosive and weapon detection capabilities normally associated with much more expensive and complex detection systems such as those based on computed tomography (CT). The systems also incorporate techniques for mitigating improvised counter measures. This work has variously been conducted with one or more of our partners: Rapiscan Security Products, L-3 Communications Security & Detection Systems and Lockheed Martin. We currently have operational QR screening systems for carry-on baggage targeting all forms of plastic explosive. The performance of these systems is a trade-off between the detection rate (DR), the false alarm rate (FAR) and the system throughput (TP).

5.1. QR BAGGAGE SCANNER T-3-02

QRSciences Limited QR baggage scanner T3-02 is a stand alone QR based explosive detection system. This is an improved version of the midsize QR baggage scanner T-3000 described in our previous paper [11]. The baggage scanner T3-02 is presented in Figure 10.

In this version the FAR was reduced by using a modified detection technique, upgraded electronics, a new mechanical design and improved software. The system requires limited initial training.

Figure 10. The QRScinces Limited QR Baggage Scanner T-3-02.

5.2. QR BAGGAGE SCANNER T-3-03

QRSciences Limited QR baggage scanner T-3-03 is also a stand-alone QR based explosive detection system. This is a second-generation QR baggage scanner. Unlike the T3-02 scanner this machine contains both QR and metal detection means. T3-02 baggage scanner is shown in Figure 11.

Figure 11. QRSciences Limited QR Baggage Scanner T3-03.

The main features of this machine are

- Operates at high speed at 200 + bags per hour.
- Highly accurate automatic detection of sheet explosives
- Low false positives (FAR)
- Countermeasure detection integrated in system

Figure 12. QXR 1000 Baggage Scanner.

5.3. BAGGAGE SCANNER QXR 1000

The QXR 1000 baggage scanner is a joint production of Rapiscan Systems (An OSI Systems Company) and QRSciences Limited. QXR 1000 utilises the QR technology combined with dual energy X-ray and countermeasures detection in a single, integrated platform. This machine provides improved checkpoint detection of a broader range of aviation treats. A greatly enhanced checkpoint screening solution is achieved by combining the automatic detection of explosives of QR method with an existing X-ray system. The unit requires no additional screeners, or checkpoint lines.

6. Conclusion

NQR technology has many benefits that are complimentary with other detection technologies such as single and multi-view, dual energy transmission X-ray, X-ray diffraction, CT and trace detection as it can increase the accuracy of automated detection. The new generation of QRSciences baggage scanners has been shown to operate effectively in the real world conditions.

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CONCEALED EXPLOSIVES DETECTOR BASED ON PORTABLE NEUTRON GENERATOR*

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1. Introduction

The problem of detection and identification of hazardous substances became very urgent during last years. Nuclear physics methods allow one to perform standoff analysis of the suspicious object, determine its chemical composition, and decide if this substance is an explosive or any other hazardous material. In particular, methods of non-destructive neutron analysis, when object is exposed to neutrons and secondary neutron and/or gamma-radiation is registered, are successfully used in some systems [1-3]. In recent years systems like these are being equipped with pulsed neutron generators instead of radioisotope neutron sources. Neutron generators have essential advantages over radioisotope neutron sources. Among them are:

- possibility to control neutron flux and its time parameters – neutron pulse repetition frequency and duration;
- high values of neutron flux (10^8 – 10^{10} n/s), which sufficiently improve the sensitivity of analysis;

* This work was supported by SNL (USA)
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H. Schubert and A. Kuznetsov (eds.), Detection and Disposal of Improvised Explosives, 205–216.

- radiation and ecological safety of generators in the “off” state, making them easy to operate and transport, since special shielding is not required;
- small mass and dimensions.

Methods using reactions of backscattering neutrons, inelastic scattering and radiative capture are rather popular for explosive detection and identification. These methods of analysis are also used in the laboratory prototype described in this publication.

2. Conceptual Design of the System

Laboratory prototype of detector based on portable neutron generator is intended for investigating possibility of detection and identification of concealed explosive contained in non-metal housing, buried in soil, placed in building walls and in other objects. It is proposed that future prototype of the system will be mobile, transported manually by 1-2 persons (i.e. maximal mass of 30 kg), occupy small space (not more than 1 m^3) and have autonomous power supply.

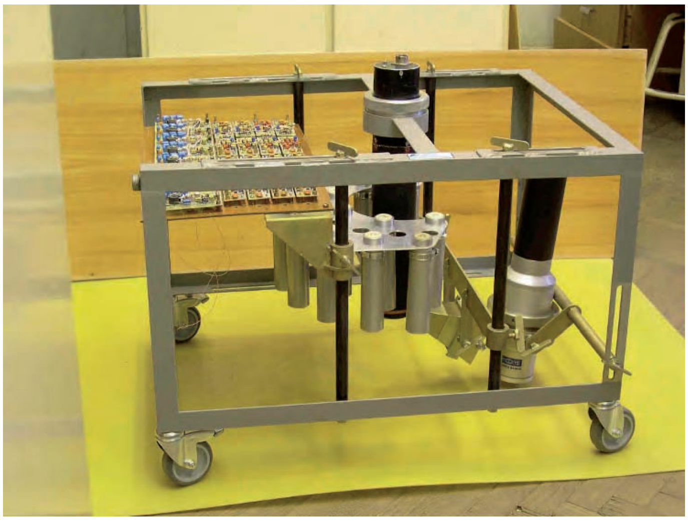

Figure 1. Laboratory prototype of explosives detector (modification 1).

The detecting part of the system consists of localization unit, identification unit, preliminary electronics and counters supply unit. The shielding device was installed to reduce gamma-background resulting from interaction of direct neutron beam of the generator with gamma-detector. General view of laboratory prototype is presented on Figure 1.

Overall dimensions of the explosives detector prototype are 700×500×500 mm. The whole construction is mounted on wheels and can be easily moved by one operator within the area of the analyzed object, and transported manually without effort from one object to another. All components of the laboratory prototype (neutron generator, localization unit, identification unit, shield) can be freely moved about each other. This allows one to select the optimum mutual arrangement of all explosive detector components during the experiments.

3. Neutron Generator

Portable neutron generator ING-17 produced at VNIIA is placed in the center of the laboratory prototype (Figure 2a).

Meanwhile, VNIIA proceeds with the development of new types of neutron generators and particularly along the path of minimizing dimensions. Small-sized neutron emitters are being created. While preserving operating characteristics, this allows one to reduce the total mass and dimensions, as well as the volume of liquid dielectric (near the target), which is a source of gamma-ray background and neutron moderator.

One such new neutron emitter (Figure 2b), which is now being applied in a ING-08 serial generator, was used to perform the first experiments with the prototype of explosive detector.

Figure 2. Neutron emitter units for two types of generators (a – ING-17, b – experimental unit based on ING-08).

Modification of the laboratory prototype of explosive detector with above generator and updated localization unit are shown on Figure 3.

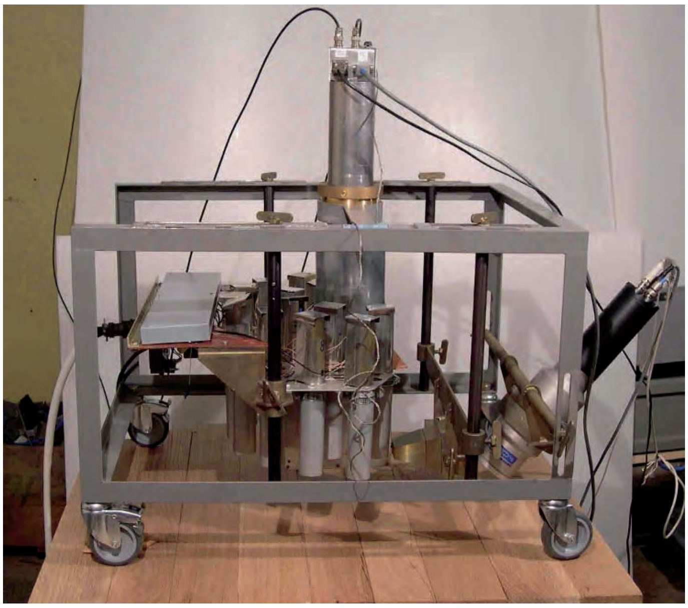

Figure 3. Laboratory prototype of explosive detector (modification 2).

Neutron generator control (turn on/off, control of parameters) was done from a PC (or a notebook) via RS-232 interface.

4. Localization Unit

Localization unit is intended for detection of backscattered slow and thermal neutrons resulted from interaction of generator neutrons with hydrogen nuclei contained in the explosive material. So the localization unit works by detecting of excess of hydrogen in the inspected medium compared to the "norm", i.e. in the absence of explosive.

Localization unit is a combination of 15 proportional ^{3}He neutron counters (Figure 4). Standard SNM-56 Russian-made counters 32 mm in diameter (working region – 100 mm, pressure – 4 atm.) were used.

Since the probability of detecting "hydrogen-containing anomaly" depends on the presence of hydrogen content contrast in anomaly and its environment, proportional counters are oriented perpendicular to inspected surface in order to enhance this contrast and to reduce the absolute background value. By the same reason the side surfaces of all counters are shielded by 1 mm-thick Cd sheet to absorb thermal neutrons coming from sides, and counter bottoms are left open to allow free penetration by neutrons scattered from the inspected region.

Since each counter is looking over its own limited region, the suggested geometry is also aimed at drawing a space map of "hydrogen-containing anomaly". It will provide more accurate localization of small hydrogen-containing items, which are then must be identified.

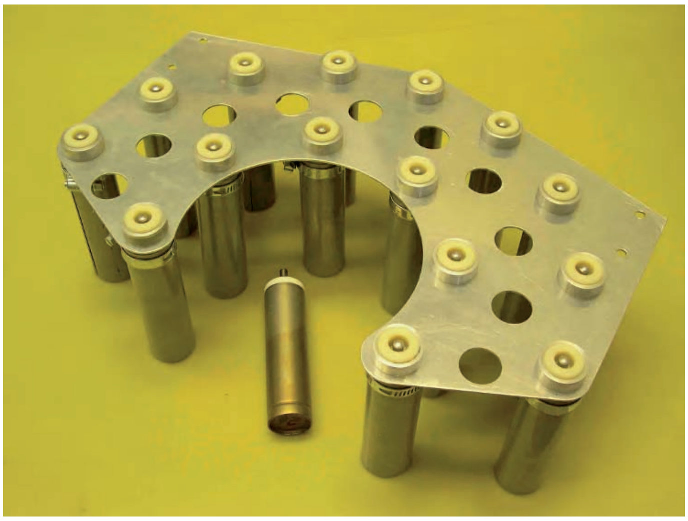

Figure 4. Localization unit consisting of 15 proportional ^{3}He neutron counters.

Mosaic of proportional counters covers up to 0.1 m^2 of the inspected surface. Six counters are arranged around the target axis (neutron source) of the neutron generator in semicircle with 10 cm radius at interval of 45º from each other; the remaining 9 counters are at distance of 18 cm from the target axis and are arranged in circle at 22.5º intervals.

5. Identification Unit

Identification of the detected "hydrogen anomaly" was conducted by using scintillation gamma-detector based on bismuth orthogermanate (BGO) crystal 63 mm in diameter and 63 mm in length, connected to a photo multiplier of FEU-183 type. Energy resolution of the detector was 10.8% (for ^{137}Cs line). With energy resolution being somewhat worse compared with popular NaI(Tl) scintillator, BGO crystal (owing to its high average atomic number Z) is characterized by high efficiency (2-5 times higher than NaI), especially for high gamma-ray energies (5-10 MeV). This is very important when measuring gamma-spectra in excitation range of carbon and oxygen lines, which are mainly used to determine presence of explosives and to identify their type.

Russian spectrometer SBS-60 ("Green Star", SRC "SNIIP") made in the form of a separate board on ISA bus and built into a personal computer (notebook) was used as a measuring and analyzing part of gamma-spectrometer. Working energy range of gamma-spectrometer was 0.4 – 12.2 MeV. Measurements of gamma-spectra from reactions of inelastic scattering of 14 MeV neutrons with explosive simulators and surrounding material, as well as reactions of radiative capture of moderated neutrons with the same materials, have demonstrated distinct peaks from silicon (1.78 MeV), hydrogen (2.223 MeV), carbon (4.44 MeV), oxygen (6.13 MeV) and other elements. Energy calibration was performed, as a rule, for hydrogen and oxygen lines.

6. Shielding

Special shield was made to reduce the effect of direct neutron irradiation of gamma-detectors, i.e. to decrease total background intensity and to improve effect/background ratio. Preliminary calculations showed, that tungsten is the most effective material that can be used for this purpose. With thickness of 30 cm it provides up to 100 times decrease of counting rate of gamma-quanta formed in BGO crystal as a result of interaction with 14 MeV neutrons. But since tungsten is rather expensive, heavy (up to 37 kg for 30 cm length and 90 mm diameter) and difficult to work with, it can't be really used as detector shield in future mobile system. We believe, that Fe, Pb and Bi are more suitable. Shielding shaped as a truncated pyramid of 12 cm total length is used in laboratory prototype of the explosive detector. Calculations showed, that use of the shield thickness above 12 cm – 17 cm does not lead to sufficient decrease of the count rate in the energy range 1 MeV – 12 MeV, since 70% - 85% of the count rate comes from reactions with the material surrounding the buried explosive.

7. Masking Materials and Explosive Simulators

Some real materials (concrete, wood, soil) of different densities and humidity were used for simulation of masking materials in which the explosive simulators were buried. In particular we used standard concrete building blocks with density (low, medium, high) of 0.7, 1.2 and 2.2 g/cm^3 respectively, corresponding to foam concrete (gas silicate type), claydite-concrete and kerb (border) stone. As for wood we used pine (0.40 g/cm^3) and oak (0.68 g/cm^3) boards. To simulate soil of various moisture we were planning to use the mixture of sand, gravel and water.

Explosive simulators were polyethylene boxes made in the form of parallelepiped with 0.6 mm-thick walls filled with the simulation mixture. RDX (400 g) was simulated by the following mixture: ammonium nitrate NH_4NO_3– 178 g, urea $(NH_2)_2CO$ – 200 g, graphite – 22 g. Trinitrotoluene (TNT) was simulated by 400 g of the following simulation mixture: ammonium nitrate NH_4NO_3 – 160 g, organic glass (Lucite) $C_5H_8O_2$ – 234 g, graphite – 6 g.

When selecting simulation mixtures we tried to maintain the weight ratio of the main components, carbon to oxygen ratio C/O and nitrogen to oxygen ratio N/O in particular. Dimensions of 400 g simulators were $15\times8\times5$ cm^3. Samples of larger size and weight (1000 g) were prepared as well. These simulators (1 kg) were used at the first stage of experiments.

8. Electronics and Data Acquisition

Electronics and data acquisition systems used in the prototype consist of circuits of preliminary electronics, detector power supply, two different spectrometers and software for data acquisition and processing.

Signal preamplifiers and shapers for neutron counters made in VNIIA were arranged just near the counters to prevent spurious noise when picking up valid signals (later these circuits were wired just on the counters).

Personal computer (notebook) with built-in circuit boards of gamma-spectrometer and 16-channel neutron time analyzer UTA-01 produced in VNIIA was used for data acquisition and analysis.

9. First Experimental Results

First experiments on detection and identification of explosive simulators in some masking materials were conducted. Search abilities of localization and identification units were investigated for the case when 1 kg TNT and RDX simulators were buried in thick layer of wood (pine and oak), light concrete (foam concrete) and dry sand.

It was established that probability of "hydrogen anomaly" detection by neutron counters, as well as reliability of identification of the detected anomaly by gamma-ray detector depended both on the burial depth of explosive simulator in the masking material and on the density and total thickness of this material. Search efficiency of both detector blocks decreases, if explosive simulators are placed inside the mass of masking material, compared to the geometry when simulators are placed under the layer of the same material. In other words, we observe the influence of additional masking layer, located deeper than the explosive simulator. In

situations like this we can't distinguish between measurements performed with simulator and without it, though explosive simulator is not buried too deep. It is evident that additional efforts shall be undertaken on optimizing geometry and suppressing background in order to increase sensitivity of the system.

First measurements were performed in the following geometry: neutron target was placed at the height of 9.5 cm above the masking surface, bottom surface of neutron counters – at 10 cm, scintillator crystal of gamma-ray detector – at 2 cm.

Time distributions measured with explosive simulators and without them were compared when searching for "hydrogen anomaly" by neutron counters of the localization unit. Program for processing these distributions was developed to visualize experimental results. It allows one to make a conclusion about presence or absence of "hydrogen anomaly" in the analyzed range after a series of paired measurements (effect-background). For this purpose 15 counters of the localization unit were arranged in 3 groups, each including 5 counters (A, B and C groups). Pulse counting was conducted by each counter and within each group, as well as integral counting in all 15 counters over the measurement time.

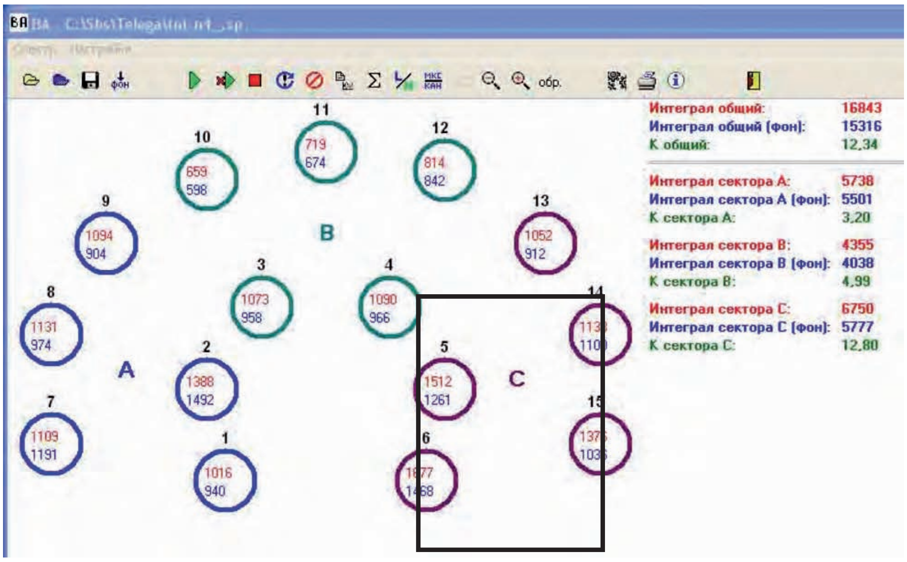

Figure 5. Display of a personal computer with results of measurements of TNT simulator covered with 3.5 cm of wood (pine). Measurement time – 3 min. Neutron flux intensity – 10^7 n/s. Simulator is outlined by rectangle in the region of the C counter group. Numbers near counters correspond to «effect» (upper line) and «background»(lower line).

These sums were compared with the data obtained for the background. The difference between measurements with simulator ("effect") and without it ("background") was shown on the monitor in K units. This value corresponds to multiplicity of excess of "effect" over "background" in units of standard deviation and indicates presence or absence of "hydrogen anomaly" (Figure 5).

One can see from Figure 5, that the integral excess of the "effect" over "background" was detected. It was detected by all counters of the localization unit, but most clearly – in the region of the C counter group, under which the explosive simulator was placed (K = 12.8). The excess is not so significant (K = 3.2) at large distance from the simulator (A group). The similar result was obtained when simulator is removed from location of C group counters to position of A group counters. So one can say that localization unit is sensitive to the presence of certain quantities of explosives hidden at different depths of different materials, and allows one to specify the position of the suspicious object within the investigated area.

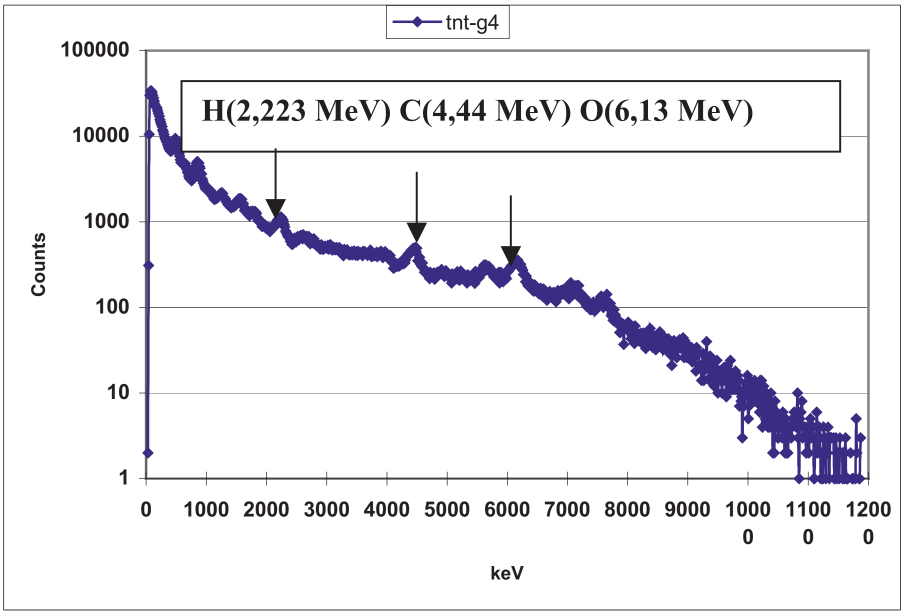

Figure 6. Energy gamma-spectrum of neutron irradiation of TNT simulator, covered by 1.8 cm of wood (pine). Measurement time – 15 min. Neutron generator intensity – 10^7 n/s.

Maximal burial depth of masking material at which explosive was detected by localization unit was 5.6 cm for wood (pine), 9.5 cm for light concrete (foam concrete) and 10 cm for dry sand.

Identification of the detected “hydrogen-containing anomaly” was conducted at neutron generator operation frequency of 10 kHz in time window 30 μs corresponding to the neutron pulse duration. Accumulation of energy gamma-spectrum from inelastic scattering reaction and partially from radiative capture reaction was carried out during the whole period of measurements (as a rule 15 min). Typical gamma-spectrum is presented on Figure 6.

Figure 6 shows the characteristic lines of hydrogen, carbon and oxygen. The data of these lines were then processed (with account of background) to make a conclusion about the type of the detected “suspicious” substance. This processing was complicated by high background level constituting up to 80%-90% of the total spectrum. Large part of the background component is due to masking material and environment.

10. Calculations

Monte-Carlo calculations showed that suggested localization unit is able to search for RDX simulator in claydite-concrete with 10% humidity and 1200 kg/m^3 density, in foam concrete with 15% humidity and 690 kg/m^3 density as well as in low density wood (pine) at different depths of sample burial (up to 15 cm). For example, results showed that an RDX simulator hidden in low-density concrete at depth of 3 cm could be detected within few seconds. But the dead zone at the edge of the detector (due to presence of 5 mm ceramic insulator) may reduce the counting rate several times (up to 3 times) and therefore increase the detection time. Calculations show, that background counting rate in intermediate density concrete (claydite-concrete with humidity 10%, density 1200 kg/m^3) is about 1.5 times higher than in low-density concrete (foam concrete with humidity 15% and density 690 kg/m^3). Experimental data obtained at the first stage of work for foam concrete in particular, are in good qualitative and quantitative agreement with calculations.

11. Gamma-Spectra Processing

Program of gamma-spectra processing is based on procedure of spectrum expansion by least-squares method (LSM). It is assumed, that the main contribution to experimental explosive spectrum comes from gamma-quanta of inelastic scattering of fast neutrons on C, N, O nuclei and from gamma-quanta of radiative capture of slow neutrons by hydrogen H nuclei.

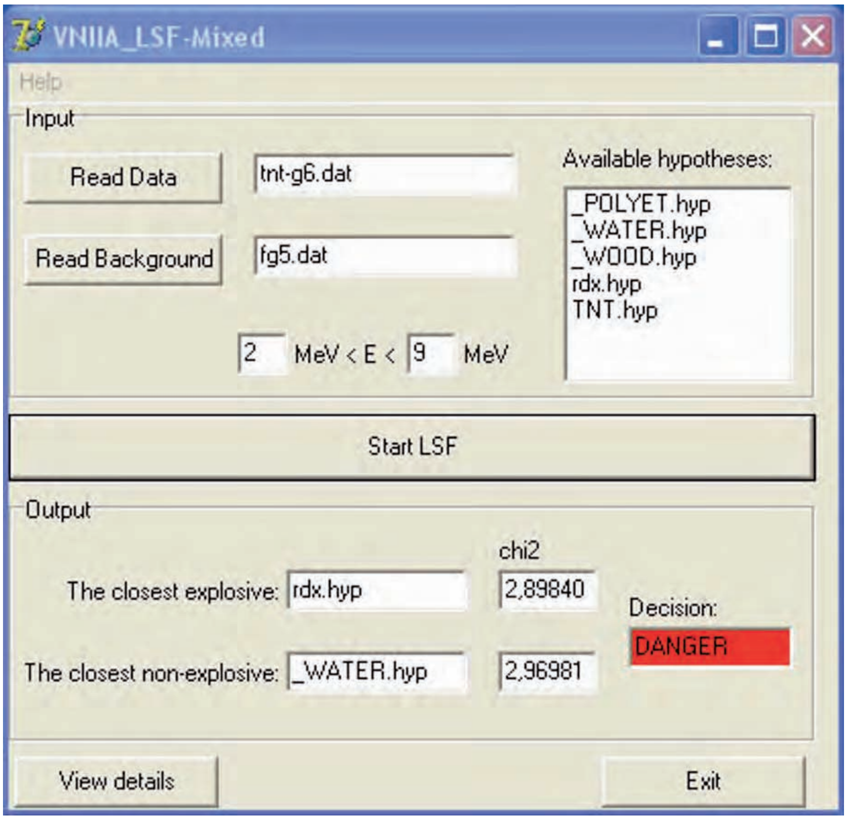

Figure 7. Display window of personal computer with results of program processing of experimental gamma-spectrum of explosive simulator buried in wood (pine) at 5.4 cm depth. Dangerous substance – RDX – was detected. The closest detected non-explosive substance was water.

Evaluation of the amount of hydrogen based on reactions of slow neutron radiative capture is qualitative, since the number of such reactions depends both on the amount of hydrogen and on the efficiency of thermalization of primary flux of 14 MeV neutrons due to collisions in the medium. Response to hydrogen is present in the form of separate component of expansion and makes it possible to compensate uncertainty of primary beam thermalization.

LSM algorithm is used in the developed program for experimental spectrum expansion into three components: background spectrum, function of response to hydrogen and function of response to one of the known substances (is taken from the library of the most typical explosives and not dangerous substances, e.g. water, polyethylene, wood etc.). A set of known

substances is automatically read from the library as program is started. The closest dangerous and not dangerous substances are determined and displayed on Output board (Figure 7).

12. Conclusion

Laboratory prototype of explosive detector on the basis of neutron generator has been created. First experiments on search and identification of explosive simulators buried in different materials were conducted.

Parameters and operation characteristics of suggested detector were determined. Obtained experimental results were compared with calculations.

It was established in particular, that search capabilities of neutron counters (localization unit) allow one to detect “hydrogen anomaly” hidden in various materials at different depths – up to 5.5 cm in low-density wood (pine), up to 9.5 cm in low-density concrete (foam concrete), up to 10 cm in dry sand – in 3 minutes with neutron generator intensity of 10^7 n/s.

At the same time gamma-detector abilities for identification are rather limited, mainly due to sufficient background from large quantity of masking material and environment. To overcome this problem we have to undertake some efforts on additional shielding of gamma-detector. But the most effective decision would be application of nanosecond neutron analysis (NNA) method with use of alpha-gamma coincidences [4].

Authors express their gratitude to L.A Korytko and I.V. Mikhailov for fruitful discussions and advices, T.O.Khasaev and S.A.Korotkov for neutron generators’ preparation, and to S.I. Klushin for help in system manufacture and experiments.

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POSSIBILITIES OF CREATING IMPROVISED EXPLOSIVES AND EXPLOSIVE DEVICES

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1. Improvised Explosive Materials (IE)

Toughening of security measures concerning industrial explosives and their components pushes criminals towards manufacturing "homemade" explosive materials and explosive devices to be used in criminal activities and terrorist acts.

Substances and mixtures capable of undergoing an explosive reaction should be distinguished from so called high explosives. When some substances (mixtures) undergo fast chemical transformation, the volume of gaseous products does not reach the level necessary for an explosion. At the same time, these substances can be blown up inside a strong metallic shell using a suitable means of initiation. In many cases terrorists and criminals do exactly that, adapting these substances to achieve an explosion.

Several kinds of improvised explosive mixtures produced from widely available components have been used in criminal practice: ammonium, potassium and sodium nitrates, potassium chlorate or perchlorate, ignition substance from match heads and others. Explosive mixes based on ammonium nitrate may also contain aluminum or magnesium powder or metallic shaving, engine oil, diesel fuel, gasoline or kerosene. Recipes of some of such improvised mixtures correspond to diamons, and they can be regarded as high explosives. Ignition substance scratched from match heads and crushed into powder can become a powerful improvised explosive mixture. Other examples are potassium permanganate with aluminum or magnesium powder, or mechanical mixtures of red lead oxide with the same metals. When ignited inside a strong metallic shell, their burning turns into an explosion. Explosive mixtures based on sodium or potassium nitrates, charcoal and sulfur are examples of homemade black powder.

H. Schubert and A. Kuznetsov (eds.), Detection and Disposal of Improvised Explosives, 217–221.

When manufacturing explosive devices, criminals usually increase their strength by adding flammable liquids to the main explosive charge. Mixtures of their vapors with air increase the strength of the explosion, cause fire etc.

The most easily accessible substances that can be used for manufacturing improvised explosives are materials based on ammonium nitrate with some additions, or different kinds of powder, especially black gunpowder. Gunpowder is a multi-component solid explosive mixture capable of burning in parallel layers without access of oxygen; during its burning mostly gaseous products are formed, whose energy cause an explosion-like expansion. There are many ways to manufacture gunpowder, which can be used both as the main explosive charge and as initiator of an explosion. Manufacturing of gunpowder is rather complicated, since explosive substances like nitroglycerine or pyroxyline ("gun cotton") must be used. Manufacturing of dynamite in home conditions is extremely dangerous, since technologically dynamite is a mixture of nitroglycerine with different substances which absorb and hold it in normal conditions.

A convenient explosive material for terrorist acts could be industrially produced and widely available flour explosive. It consists of 80% RDX and 20% of conventional wheat flour. Visually, even under microscope, the flour explosive is absolutely indistinguishable from wheat flour, and it is often kept by criminals in standard flour package. It can be used as an explosive both dry and with water added to plasticize it for giving it any necessary shape depending on the task.

One must also mention another initiating explosive: mercury fulminate, which can be produced according to a known recipe. Mercury fulminate is dangerous to handle, since it easily ignites from impact, friction, contact with flames, etc.

One can conclude, that production of both improvised explosive mixtures and improvised initiating substances outside laboratory is quite possible.

2. Improvised Explosive Devices (IED)

An explosive device is a one-time device, in which the damage is achieved through use of energy of an explosive charge, explosive substance or a mixture. It consists of main and auxiliary elements. The main element is the explosive charge and means of its initiation. The charge and means of its initiation are always structurally united with each other. Additional elements of an explosive device are mechanisms for its triggering, the shell surrounding the charge, the body of the device, additional injurious elements. In all improvised explosive devices individual combination of

materials is used. An improvised explosive device is produced using non-standard (“homemade”) components, substances and devices. In many cases the only “improvised” part of IED is the triggering device.

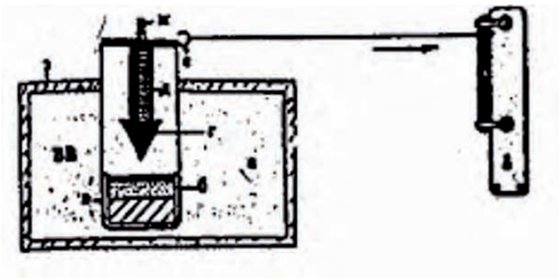

Figure 1. Schematic view of a “release” type IED.

A schematic example of an improvised explosive device is shown at Figure 1; it consists of an explosive charge, a detonator cap placed in a tube, above which there is a firing pin on a compressed spring. When released, the firing pin hits the detonator, which ignites the explosive charge.

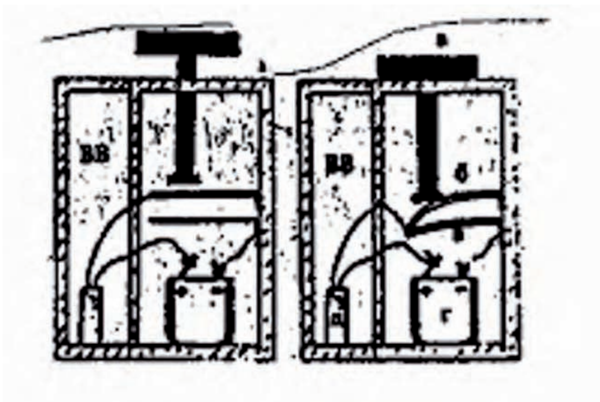

Figure 2. “Screw-down” type IED.

Another type of the triggering device is a “screw-down” IED shown on Figure 2. It is based on an electrical detonator, which is triggered by two contact electrodes.

Both above IEDs explode immediately after they are triggered. In many cases the explosion must be carried out at some particular moment of time.

The simplest “sun-driven” IED is shown at Figure 3. The explosion is initiated when the sunlight focused by a converging lens ignites the initiating explosive (usually powder).

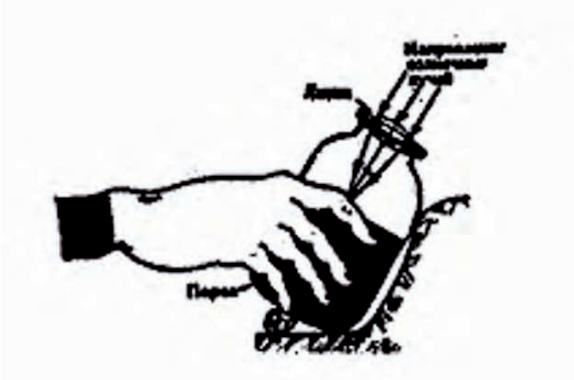

Figure 3. “Sun-driven” IED.

The explosion can be also delayed chemically, e.g. by acting with acid on the triggering device. Among most widely used IEDs with delayed explosion are those using an alarm clock, which closes an electric circuit of a detonator.

There exists a large variety of “surprise”-IEDs, when an explosive and a detonator are located inside some innocently looking object, which can be unknowingly used by the victim.

Some known examples are:

- Book explosive: IED is placed inside a cavity in a book.
- Lamp explosive: IED disguised as a kerosene lamp.
- Pen explosive: the rod is replaced by tetryl.
- Billiard ball explosive: a lead azide charge is placed into a drilled hole; detonates even at a soft touch by a cue.
- A smoking pipe explosive: a pipe is filled with tetryl.

One must specially note a danger from explosives placed in mail items (parcels, letters), which usually have an explosive charge, the power supply, a switch, and a trigger mechanism, all connected by wires.

Improvised anti-vehicle and anti-person mines are usually based on conventional explosives (e.g. TNT) and pressure-sensitive detonators placed into a wooden box.

3. Conclusions

Neutralization of improvised explosive devices can be very dangerous, since their trigger mechanism is unknown.

Methods of search and detection of improvised explosives do not differ significantly from those used for industrial explosives: electromagnetic location, vapor detection, nuclear-physical methods.

A characteristic feature of many IEDs is use of electrical detonators and capsules of “shock” type with metallic (copper, aluminum or iron) shells, which is an unmasking factor for electromagnetic and nuclear-physical methods.

Of great help will be an efficient portable x-ray device for detailed operative inspection of any explosive devices, including improvised, in order to determine the type of its triggering system. Such device will be especially valuable for inspection of mail items and “surprise” bombs.

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INVESTIGATION OF POSSIBILITY TO DETECT THE DETONATORS OF THE EXPLOSIVE DEVICES BY MEANS OF ED XRF APPROACH

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Capsule-detonators (CD) and Electro-detonators (ED) initiate the action of the explosive devices enclosed in different objects including luggage and postal parcels.

The main substance of the detonator components is usually fulminate of mercury or chemical compound on the basis of lead, the contents of 0.3±0.1 g is typical for a single device [1].

XRF approach is widely used for a long period of time for heavy element detection in various objects [2]. Fluorescent K- and L-series are used as analytical lines for these elements. There is a proposal (Ref. [3]) to use XRF approach for searching and detection of CD and ED as well as lead-filled ammunition in the luggage and postal parcels.

Previously for the excitation of mercury or lead lines isotope sources like ^{123m}Te and ^{192}Ir were used, and the detection systems were built on the basis of NaI(Tl) crystals, Multiwire proportional chambers or Ge(Li) detectors. A barrier with atomic number about 6-7 and of 20-25 mm size represents the maximal thickness for the detection of mentioned heavy elements in this case.

At present the use of radioisotope sources in the instruments is essentially limited due to a need to ensure safety during their storage and use.

From the other hand an X-ray tube with appropriate anode voltage is probably better source for the excitation of heavy elements according to exploitation conditions and from the point of view of high density of the primary photon flux. It is important to note that the existing installations for the luggage inspection at the airports are equipped with X-ray tubes more or less suitable for solving the problem discussed.

We have carried out experimental and theoretical investigations on the applicability of XRF approach to the detection of heavy elements behind a barrier made of material with atomic number about 7. X-ray tubes with anode voltage of 30 kV and 160 kV were taken into consideration.

H. Schubert and A. Kuznetsov, (eds.), Detection and Disposal of Improvised Explosives, 223–226.

Experiments were made to obtain intensity of lead lines Lab versus barrier thickness up to value of 0.24 g/cm^2, which corresponds to 30 standard sheets of paper. In this case the excitation source was an X-ray tube with anode voltage of 30 kV (ED XRF instrument X-Art produced by Comita Co., St.Petersburg). The duration of single measurement was 100 s. Lead sample thickness behind the barrier was 1 mm but the escape depth for the mentioned fluorescent radiation was less than 0.1 mm. The area irradiated was about 50 mm^2.

The results are demonstrated at Fig. 1. From these results one can conclude that with the help of this method heavy elements can be detected in the postal correspondence like letters in envelopes or parcels made of light cardboard.

Further results for a golden foil and surrounding material of atomic number 7.7 were obtained with the use of calculations (Monte Carlo approach).

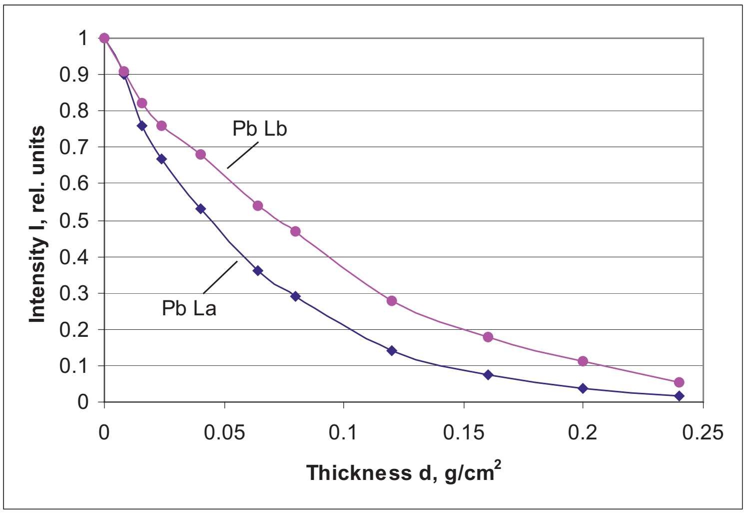

Figure 1. Pb *L*-series intensity versus barrier thickness.

The geometry of these calculations is demonstrated at Fig. 2. All parameters are shown at the figure. In the process of calculations the foil of given thickness is moving along the coordinate corresponding to the material depth. As an example at Fig. 3 the detected spectrum is shown which includes excited Au K-series fluorescent radiation and scattered radiation. 20 m foil is placed at a depth of 5 cm in the object of 20 cm thickness. At the same figure the primary spectrum of the X-ray tube with tungsten anode and 160 kV anode voltage from [4] is shown by dashed line.

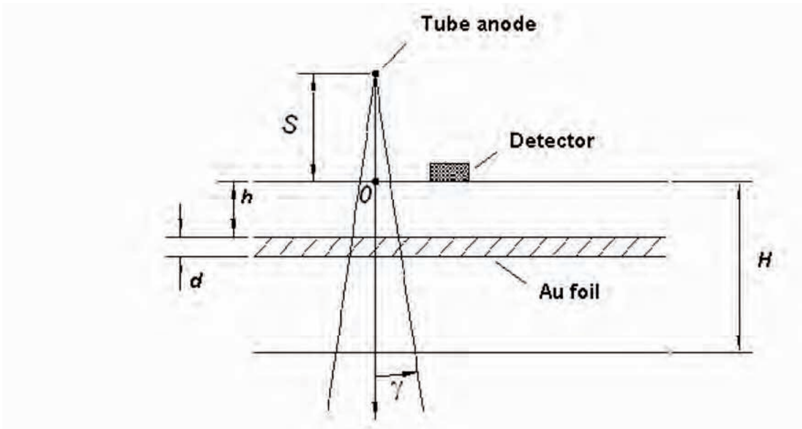

Figure 2. Geometry of calculations. h – foil position along the z-axis. d – foil thickness. H – material thickness.

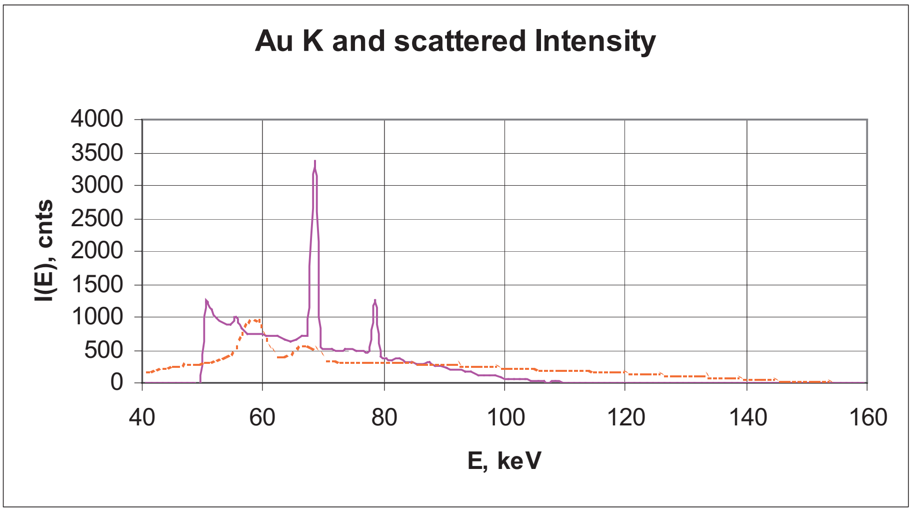

Figure 3. Dashed line - X-Ray tube spectrum. 10^6 primary photons. d=20 μ, h=5 cm, H=20 cm.

Calculated results for the total intensity of radiation detected and Au K fluorescent radiation intensity versus the 20 m foil position are demonstrated at Fig. 4. All calculations are made for 10^6 incident photons.

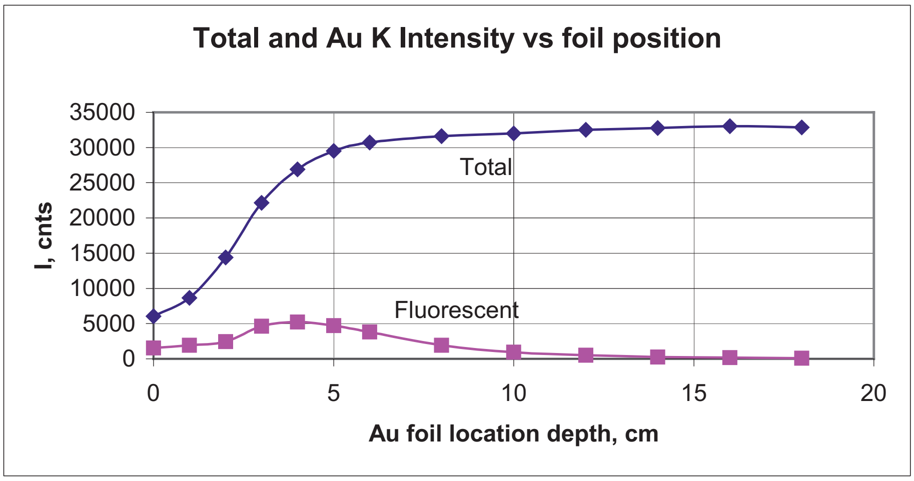

Figure 4. 10^6 primary photons, d=20 m, H=20 cm.

According to these calculations it is clear that CD and ED containing mercury or lead can be detected through their K-lines in the light material at a depths up to 10–15 cm. Of course it is necessary to use a spectrometer with high-energy resolution, for example on the basis of HPGe detector.

To develop an instrument realizing the method described it is necessary first to make experimental work with an X-ray tube at anode voltage of 100 kV and higher. Such instrument can be applied to the problem of testing the postal correspondence on the presence of the explosion devices. The process of testing for separate pieces as well as for a system of correspondence flux should be available. It is also possible to use such instrument for the analysis of passenger’s luggage at the airport.

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EFFECT/BACKGROUND CORRELATIONS IN NANOSECOND NEUTRON ANALYSIS

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Abstract. Nanosecond Neutron Analysis (NNA) technology is used for detection, identification, and localization of explosives. The main source of background in NNA are gamma-rays induced by fast tagged neutrons in non-explosives materials, and gamma-rays produced by non-tagged neutrons slowed down or emitted at the large angles to the trajectories of tagged neutrons. The results of experimentations and numerical simulation of NNA carried out in Russian Research Center "Kurchatov Institute" are reported. This work has been implemented for the geometry of experimental setup for explosives detection. The energy and time dependencies of the detected gamma-rays were obtained due to the selection of events by NNA technology. The comparison of theoretical and experimental data is considered, and the ways of improvement of their convergence are discussed. The basic components of background induced by neutron interaction with various objects (neutron generator units, shielding, gamma-detector) as well as sources of time fluctuations affecting the total time resolution are examined. The experimental and theoretical results show that the NNA technology provides effective (by 2-4 orders of magnitude) suppression of background by spatial and time discrimination of events.

1. Introduction

One of the main challenges of neutron standoff detection technologies is the high level of background. In recent years, the nanosecond neutron analysis (NNA) technology is rapidly progressing. This technology allows one to decrease the background by spatial and time discrimination of events.

H. Schubert and A. Kuznetsov (eds.), Detection and Disposal of Improvised Explosives, 227–236.

The NNA technology is the most effective for solving such tasks as the detection, identification, and localization of high explosives (HE). Inelastic scattering of fast neutrons induces gamma-rays with discrete (characteristic) energies, which gives information on the presence of carbon, nitrogen, and oxygen (the basic chemical components of explosives) in the inspected object.

The typical scheme of NNA is given in Figure 1. Neutrons and alpha-particle are emitted at the $T(d,n)^4He$ reaction when deuteron beam bombards the tritium target of the neutron generator (NG). The vectors of neutron and alpha- particle escape are uniquely correlated. The position- and time-sensitive alpha- detector measures the time and position of incident alpha-particles, thus providing the angle and time of neutron escape (“tagging” the neutron). The gamma-detector array records gamma-rays induced by “tagged” neutrons interaction with the matter. As far as the positions of detectors are known, and the velocities of tagged neutron and gamma-ray are defined, the location of gamma-ray escape along the tagged neutron trajectory can be determined by the time of gamma-ray recording with respect to the time of neutron generation (time of associated alpha-particle recording).

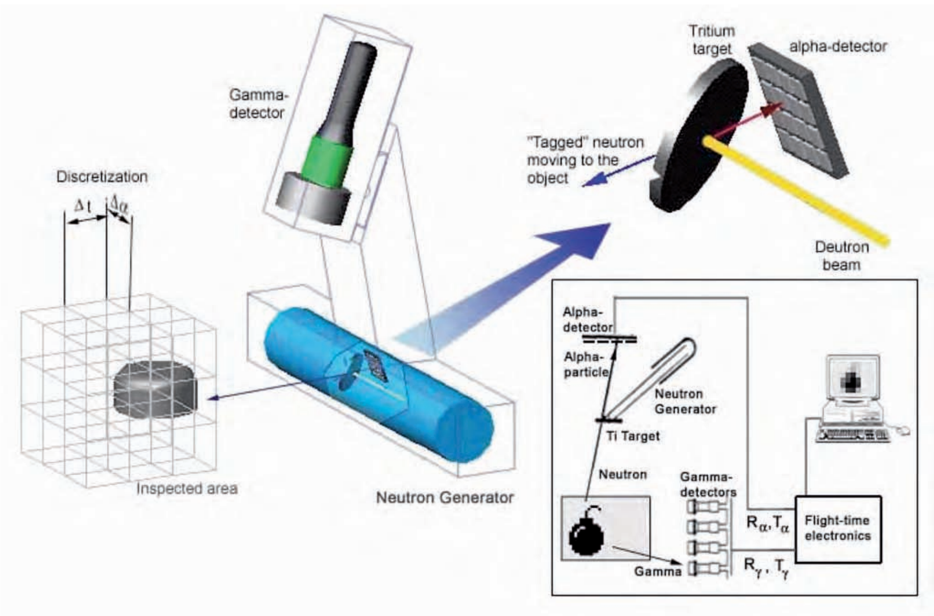

Figure 1. Neutron Nanosecond Analysis Layout.

The composition of the object is identified by analyzing the spectrum of selected gamma-rays. The most informative are gamma-rays induced by inelastic neutron scattering on carbon, nitrogen, and oxygen nuclei. The energies and cross-sections of gamma-ray production are given in Table 1.

The Data Acquisition and Control (DAC) unit (lower right corner of Figure 1) traces the gamma-ray energy and recording time t_γ, as well as pixel number R_a and recording time t_α of the alpha-particle that "tags" the neutron. Computer processes the data and displays the 3D image of the deduced elemental composition of the object on the monitor.

The neutron track is traced by alpha-detector with the angle accuracy $d\Omega$. Thus, the event can be located at some discrete volume (voxel) $dL \times d\Omega R \times d\Omega R$, where R is the distance between the voxel and the alpha-detector. The volume of the inspected object can be divided into such voxels (Figure 1). The intensity of "useful" events is proportional to the nuclear density of sought chemical elements. It is then possible to reconstruct the 3D image of elemental composition of the object and assess the nuclear density of carbon, nitrogen, and oxygen (or ratios of O/(C+N+O), C/(C+N+O), N/(C+N+O) as well as those for other chemical elements.

Table 1. Reaction cross-sections in NNA for carbon, nitrogen and oxygen.

Element	Energy E_γ, MeV	Cross- section of neutron inelastic scattering accompanied by gamma-ray emission with the energy E_γ, millibarn
Carbon	4.4	200
Nitrogen	2.3	40
	5.1	90
Oxygen	6.13	140
	6.92 & 7.12	100

2. Experiment

The hardware measuring module (HMM) and supporting software were developed in RRC "Kurchatov Institute" by the order of All-Russia Research Institute of Automatics (Moscow) for testing the neutron generators with built-in alpha-detectors. The diagram flow of HMM is given in Figure 2. It is implemented according to backbone-modular principle. It receives signals from built-in alpha-detector (one channel) and external control detector (time and amplitude channels). The neutron and gamma-detectors of various types can be used as the control detector. For

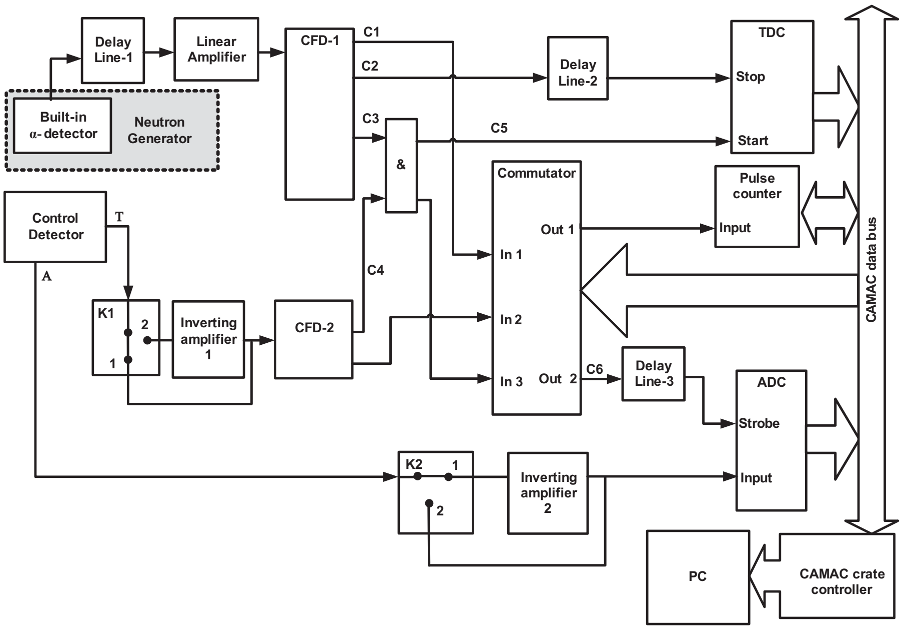

Figure 2. The flow diagram of HMM.

adjustment of the polarity and duration of the control detector signal, the amplifiers, invertors, and delay lines are used.

The constant fraction discriminator CFD-1 generates:

- C1 pulse for commutator to issue the strobe;
- C2 pulse coming to the Time-Digital Converter (TDC) as a STOP pulse;
- C3 pulse that is used in conjunction with the C4 pulse (from the control detector) to generate C5 pulse marking the presence of alpha-gamma or alpha-neutron coincidences.

The signal from input time channel of control detector triggers the measurement of timing of coincidences. The start is counted from the pulse T of the control detector. Coming to the CFD-2, it produces the C4 signal. In presence of alpha-detector signal during the time gate, the C5 pulse from "&" unit starts the TDC. The commutator unit produces C6 pulse to generate the strobe setting the proper time of ADC acquisition (measuring the amplitude of the control detector signal). The HMM includes also high voltage supplies for detector and controller for PC interfacing. Each event (coincidence between alpha- and control detectors) is represented by 4 bytes (2 bytes – amplitude, 2 – time). The HMM can work also in the

"non-coincidence" mode recording all signals coming to the amplitude input of control detector. The software provides the acquisition of events, on-line display of accumulated data and their storage.

During tuning of HMM, the intrinsic time resolution Δt of the device was measured. The signals from detector were simulated by pulses from high-stable pulse generator passed through integrating- differencing circuits. The value of Δt did not exceed 0.2 ns for wide range of amplitude of input signal (30-300 mV for alpha-channel, 30-3000 mV for control detector channel).

For testing the HMM, the experimental model of explosives detection device was used. The model included all the basic unit of NNA detection system. The layout of the model is given in Figure 3. The graphite or melamine ($C_3N_3(NH_2)_3$- nitrogenated substance of 1.2 g/cm^3 bulk density) imitated the explosives. The NG with the sealed neutron tube was developed in VNIIA. It provided the continuous neutron flow with the intensity up to 2×10^7 s^{-1}. The four-pixel built-in alpha-detector was developed in JINR, Dubna, Russia [1]. It consists of four $YAlO_3$ (YAP(Ce)) scintillators installed near the neutron production target. The scintillators transmit the optical radiation induced by alpha-particles through the glass window to the ultra-fast PMTs. Only one channel was used in experiments.

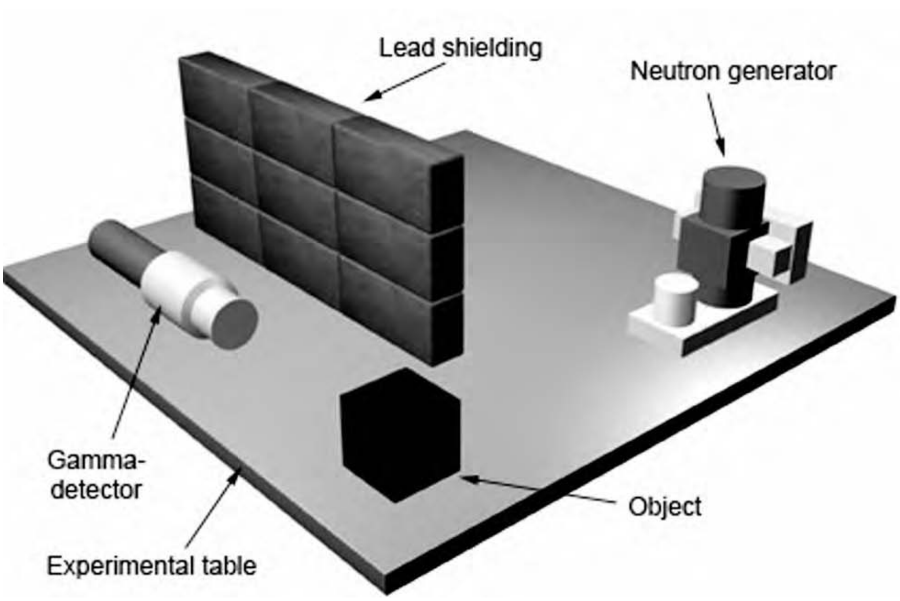

Figure 3. The layout of experiment.

The gamma-rays were recorded by gamma-detector incorporated BGO scintillator, PMT and electronic unit for output signal processing. It provides the time (up to 2.5 V, 50 ns rise time) and amplitude (up to 5 V, 500 ns rise time) signals. The signals from alpha- and gamma- detectors were discriminated by amplitude and by time of coincidence. The width of time gates was as high as 100 ns. At the presence of the signals from both detectors within this time interval, the “event” was recorded and stored in memory.

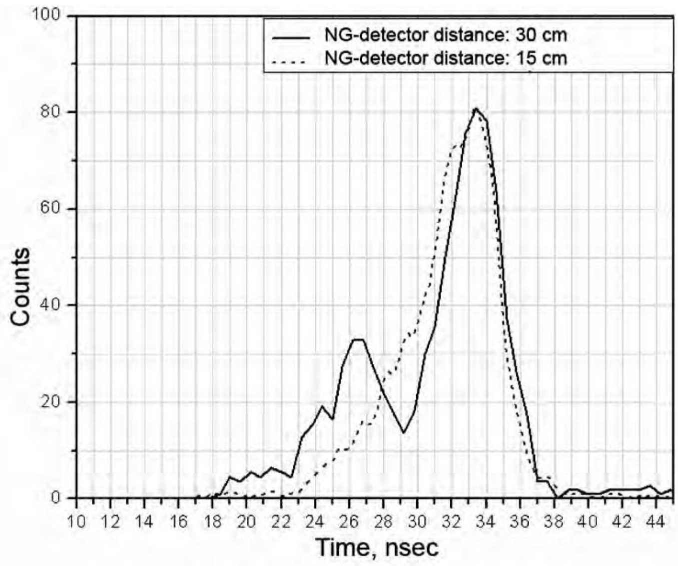

Figure 4. Time spectrum of alpha-gamma coincidences.

A portion of “tagged” neutrons are scattered at the copper holder of target and NG inducing background gamma-rays. To prevent this “correlated” background, the lead shielding between NG and gamma-detector was used. The “uncorrelated” background includes:

- Gamma-rays induced by “non-tagged” neutrons (emitted at the high angles to the “tagged” neutron paths; the associated alpha-particle is not detected by the alpha-detector).
- Gamma-rays emitted through the reactions other then inelastic scattering (radiative neutron capture, radioactive decay, etc.).

As far as all events beyond this time gate are rejected by the HMM, these components of “non-correlated” background are highly reduced in NNA.

The time spectrum of alpha-gamma coincidences is given in Figure 4. A good time separation of “useful” events from “correlated” background at

the 30 cm distance can be seen. The time resolution is about 3.5 ns. When the distance is 15 cm, the "correlated" background overlaps the "useful" events that results in broadening the time distribution.

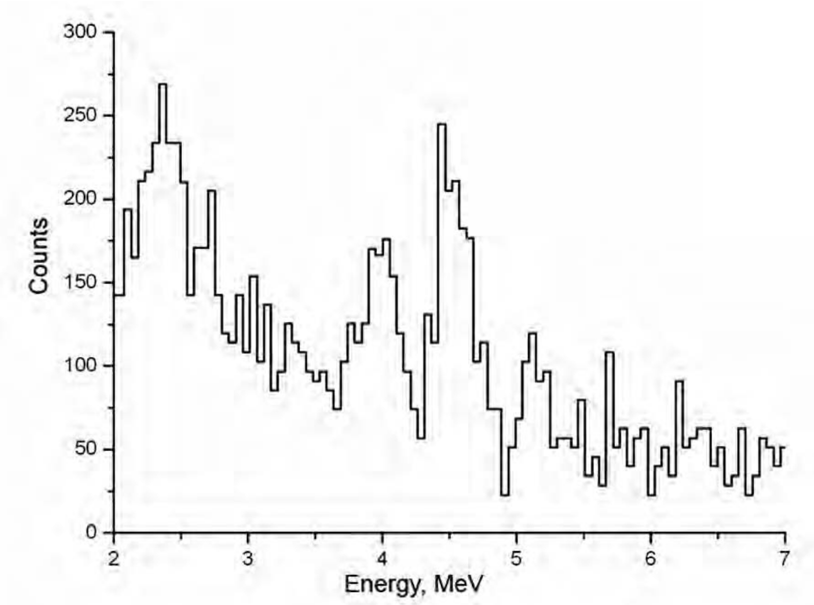

Figure 5. Gamma-spectrum from melamine in the NNA mode.

Figure 5 displays the gamma-spectrum taken from graphite and melamine in the NNA mode. The peaks of inelastic neutron scattering by carbon (4.4 and 3.9 MeV) and nitrogen (2.3 and 5.1 MeV) sufficiently exceed the background level. For comparison, the gamma-spectrum taken from graphite in the NNA mode (lower curve) and total gamma-spectrum (upper curve) are shown in Figure 6. The two-peak structure of the NNA spectrum is evident; the main peak corresponds to the 4.4 MeV, and 3.9 MeV peak is due to the annihilation single escape (SE). The total spectrum is the superposition of peaks and background exceeding the "useful" signal level by 2 orders of magnitude.

For assessment of limits of time resolution of the experimental model, the fast neutron plastic detector was connected to the control detector inputs. The detector was positioned along the axis corresponding to the maximal intensity of tagged neutrons. The distance between NG and neutron detector was varied from 15 cm to 30 cm. The time spectrum of alpha-neutron coincidences are given in Figure 7. The time between 2 peaks (taken at the distance 15 cm and 30 cm) is around 3 ns. It corresponds to the time required for 14 MeV neutron to pass 15 cm.

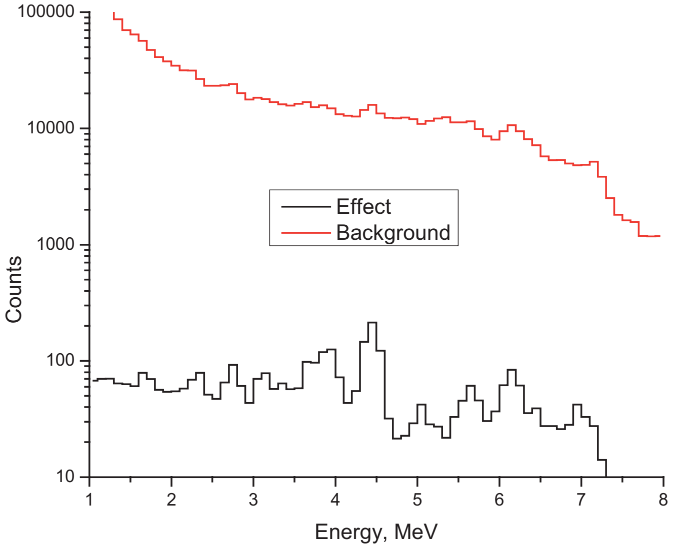

Figure 6. Comparison of gamma-spectrum taken in the NNA mode (lower curve) and total gamma-spectrum (upper curve).

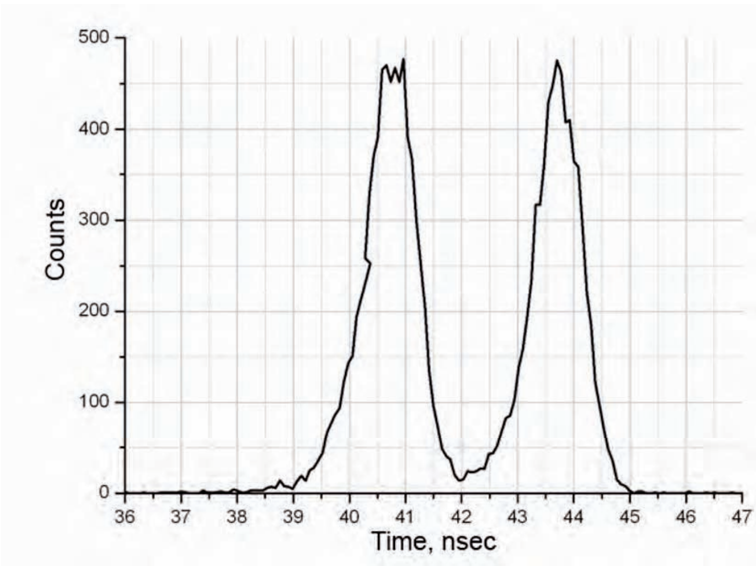

Figure 7. Time spectrum of alpha-neutron coincidences.

3. Mathematical Modeling

For assessment of contribution of each component of NG and experimental setup to the time and amplitude dependencies (Fig. 4-6), the numerical simulation of gamma-neutron transfer and recording was carried out. The real apparatus and items of experimental setup were simulated by parallelepipeds, cylinders, rings. In total, 12 modeling primitives were considered (the NG is the combination of five primitives). The GEANT3.21 [2] program package (upgraded for solving the NNA problems) has been used. The output parameters included the time of recording (referred to the time of associated alpha-particle recording), energy of gamma-rays absorbed by gamma-detector, source (nucleon and object) of the gamma-ray. Figure 8 displays the time spectrum of gamma-rays emitted from various objects. It can be seen that the basic component of background are gamma-rays induced by scattering of tagged neutrons by NG elements (target holder and casing). It is evident that at the time resolution of 1 ns the "useful" signals can be well separated against this background component.

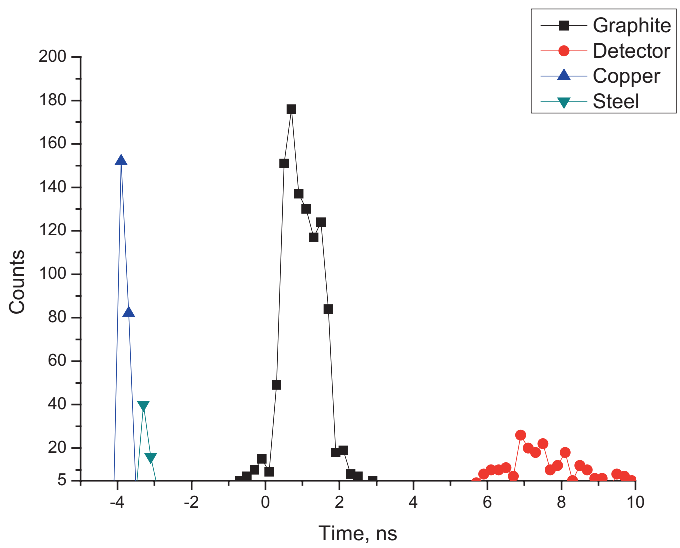

Figure 8. Calculated time spectrum in the NNA mode.

Table 2. Contribution of elements of the experimental model to the gamma-rays spectrum.

	NNA mode		No coincidences	
	Graphite	Melamine	Graphite	Melamine
Object	59,73%	54,12%	0,79%	0,35%
Target holder (copper)	13,14%	20,06%	13,44%	13,87%
NG casing	3,44%	5,09%	10,81%	10,91%
Oil (of NG)	<0.1%	<0.1%	0,57%	0,60%
Gamma-detector	22,39%	19,16%	64,35%	64,72%
Table	0,25%	0,75%	1,58%	1,56%
Lead shielding	0,96%	0,67%	3,05%	2,95%
Air	<0.1%	<0.1%	5,41%	5,05%
Nitrogen			3,68%	3,52%
Oxygen			1,72%	2,52%

Table 2 shows the contribution of main elements of experimental model to the gamma-rays spectrum without NNA (no coincidences) and in the NNA mode. It is evident that without NNA the intensity of gamma-rays from all the considered elements (including air) is much higher than from the object. From the comparison of the given data one can conclude that the NNA provides effective (by 4 orders of magnitude) suppression of background by spatial and time discrimination of events.

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USE OF NON-LINEAR JUNCTION DETECTORS TO ENSURE THE SAFETY OF IED SEARCH

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About one third of terrorist explosive devices (ED) that are used in the world's "hot spots" are radio-controlled. Such devices account for 60-70% of those used for mining roads. Explosive devices are placed on mountain passes, canyon exits, road intersections, serpentines, steep downward/ upward roads, turns; They are also placed on roadbeds, bridges, tunnels and other road facilities.

It is very difficult to counter these acts of sabotage, the more so since the intensive development of radio-electronics allows terrorists with an average expertise to make radio-controlled devices at home. They can make use of inexpensive radio components/modules or ready industrial products (radio-controlled models, car alarms, pagers, etc.). Thus manufacturing of radio controlled ED ceased to be a prerogative of the defense industry.

Portable NLJD is the most efficient equipment for locating radio-controlled explosive devices (RED) in field conditions.

The EAGLE detector (NR-900K, see Figure 1) manufactured by ECMC-1, Moscow, Russia, has the best search characteristics as compared to existing Russian and foreign NLJD models. The detector is being successfully used to counter terrorism both in Russia and overseas. Specially designed for demanding field environments, the detector locates RED at distances of 3-40 meters.

However, there are some hypothetical threats for a human operator, such as:

- RED self-triggering caused by NLJD SHF probing signal.
- RED remote triggering by terrorist during its disposal.

RED self-triggering can actually be initiated by any search device that generates a probing field (i.e. when using induction metal detectors, geo-radars, X-ray TV devices, and even search probes). In other words, NLJD is no exception here.

H. Schubert and A. Kuznetsov (eds.), Detection and Disposal of Improvised Explosives, 237–239.

RED self-triggering can be caused by SHF probing signal that is detected by RED non-linear components. It was found experimentally that RED can be self-triggered when the SHF field density is not lower than 100-120 W/m^2. In practice, this can be achieved when NLJD antenna is as close as 1-1.5 m and less to an RED. The most primitive improvised RED with non-shielded electronics are most likely to detonate. However, these RED pose threat to the terrorists as well during their setup and check-outs because their self-triggering can be caused by any outside SHF source (cell phones, airplane radiolocation systems, etc).

To lower the risk of RED self-triggering the EAGLE detector is provided with a button to decrease the radiated impulse power from 200 W to 30 W.

Figure 1. NLJD "Eagle" in the field.

During the search when the energy contact with RED is established, the operator brings the radiated power down to 1/6 of its initial magnitude and then close in on RED location in the safe mode. The average radiated power is very small – 130 mW, i.e. lower than that of a cell phone. For training purposes the IKMTs-1 company has manufactured the self-triggering RED imitator OSA (WASP) (see Figure 2).

When a specified SHF energy threshold is exceeded the WASP generates acoustic and light signals to indicate self-triggering. The NLJD

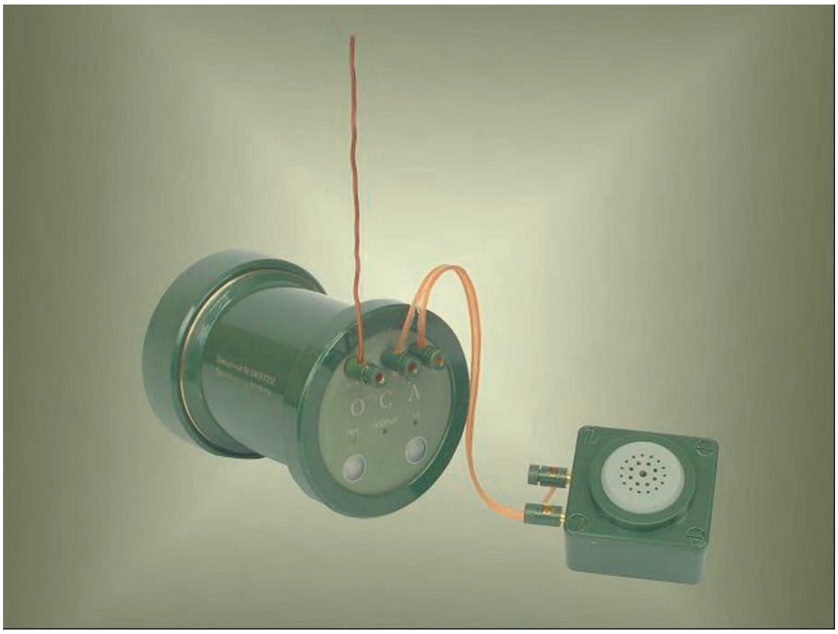

Figure 2. Self-triggering RED imitator "Osa" ("Wasp").

trainee shall locate the WASP without causing its self-triggering. The WASP imitator is used in Chechnya for sapper training.

Over 200 NLJD "Eagle" are used in many regions across the world. Dozens of RED have been located. No official records of NLJD operators been killed due to RED self-triggering have yet been presented.

A greater risk for NLJG operator is posed by RED detonated by the terrorist during RED disposal. Often RED is observed by the terrorist, who chooses the object and time of detonation. Generally, the terrorist with a remote control positions himself at 150-400 m from the RED. The most efficient way of protecting the NLJD operator from the RED blast is to use broad-band jammers to suppress the terrorist's control signal. Note that the jammer does not interfere with NLJD operation. The Russian made "Pelena" jammers meet these requirements. It is produced in both transportable and portable varieties. The frequency range is 20 – 1000 MHz; the output power – 64 Wt. The RED control signal is effectively suppressed at distance 25 – 30 m, which saves the operator's life in the majority of RED self-triggering.

Thus The RED search with the use of NLJD is a trade-off operation for the operator. However, the NLJD "Eagle" power adjustment capability and the use of broad-band jammers tend to lower the risk during de-mining operations.